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Treatment of Volatile Organic Compounds in Drinking Water

(U.S.) Municipal Environmental Research Lab.
Cincinnati, OH

May 83

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16. ABSTRACT

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tri- and tetrachloroethylene; cis- and trans-1,2-dichloroethylene; 1,1-dichloroethylene; vinyl and methylene chloride; 1,1,1-trichloroethane; 1,2-dichloroethane; carbon tetrachloride; benzene; chlorobenzene; 1,2-, 1,3-, and 1,4-dichlorobenzene; and 1,2,4-trichlorobenzene.

Conventional water treatment will not generally reduce the concentrations of these compounds, but they can be reduced by aeration, adsorption on granular activated carbon or synthetic resins, or combinations of these processes. Boiling can also be effective for home treatment of these contaminants.

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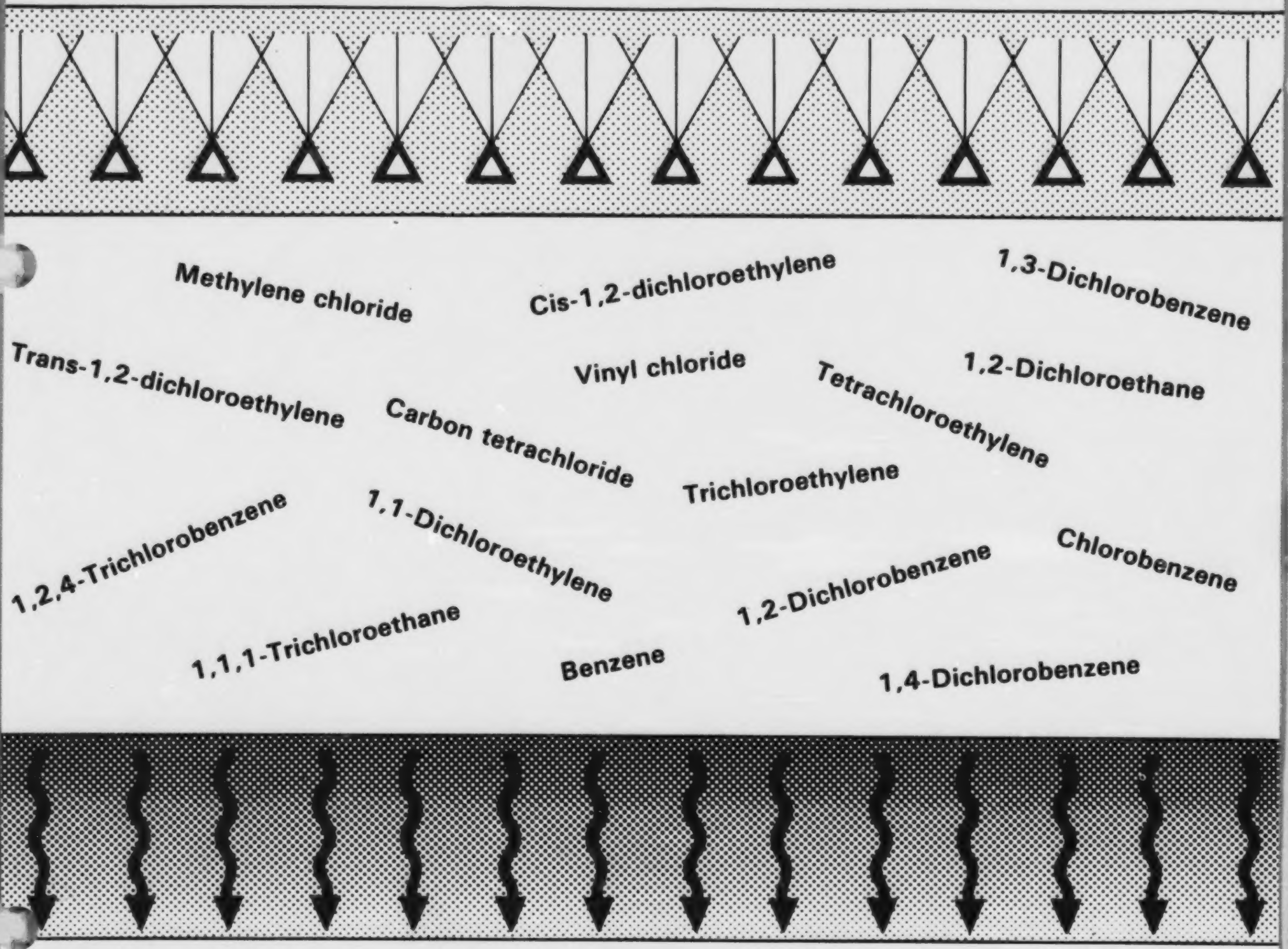
Methylene chloride
Cis-1,2-dichloroethylene
1,3-Dichlorobenzene
Trans-1,2-dichloroethylene
Vinyl chloride
1,2-Dichloroethane
Carbon tetrachloride
Tetrachloroethylene
Trichloroethylene
1,2,4-Trichlorobenzene
1,1-Dichloroethylene
Chlorobenzene
1,2-Dichlorobenzene
1,1,1-Trichloroethane
Benzene
1,4-Dichlorobenzene

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TREATMENT OF VOLATILE ORGANIC COMPOUNDS IN DRINKING WATER

by

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FOREWORD

The U.S. Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimonies to the deterioration of our natural environment. The complexity of that environment and the interplay of its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution; it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems to prevent, treat, and manage wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, to preserve and treat public drinking water supplies, and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research and provides a most vital communications link between the researcher and the user community.

Volatile organic compounds are increasingly being detected in drinking water sources, and particularly in ground waters once thought to be pristine. These compounds are not disinfection by-products, but pollutants entering our ground water aquifers through improper chemical storage/handling, or wastewater disposal activities. This report describes some of those contaminants and examines the results of water treatment research to minimize their concentrations at the consumer's tap.

Francis T. Mayo, Director
Municipal Environmental Research
Laboratory

ABSTRACT

Volatile chlorinated and non-chlorinated compounds occur in both untreated and treated drinking water. Because volatilization is restricted, ground waters rather than surface waters are more likely to have high concentrations of these compounds. This document reviews properties, occurrence, and experiences, particularly laboratory and pilot scale, with the control of the following compounds:

> tri- and tetrachloroethylene; cis- and trans-1,2-dichloroethylene; 1,1-dichloroethylene; vinyl and methylene chloride; 1,1,1-trichloroethane; 1,2-dichloroethane; carbon tetrachloride; benzene; chlorobenzene; 1,2-, 1,3-, and 1,4-dichlorobenzene; and 1,2,4-trichlorobenzene

Conventional water treatment will not generally reduce the concentrations of these compounds, but they can be reduced by aeration, adsorption on granular activated carbon or synthetic resins, or combinations of these processes. Boiling can also be effective for home treatment of these contaminants.

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SECTION 1

INTRODUCTION

Sixteen synthetic organic compounds--trichloroethylene, tetrachloroethylene, cis- and trans-1,2-dichloroethylene, 1,1-dichloroethylene, vinyl chloride, 1,1,1-trichloroethane, 1,2-dichloroethane, carbon tetrachloride, methylene chloride, benzene, chlorobenzene, 1,2-, 1,3-, and 1,4-dichlorobenzene, and 1,2,4-trichlorobenzene--are undergoing review for possible inclusion in the National Revised Primary Drinking Water Regulations (1).* This report relates some occurrence experiences, describes the general properties of these organic compounds, and summarizes some of the available treatment data. Most of this treatment information was obtained through laboratory and pilot scale studies in which aeration and adsorption were selected as treatment options. Cost estimates for these treatment processes were made by combining theory with the available empirical data.

This report is intended to be used as a "working document" whereby updated information, particularly from full scale treatment installations, can be inserted in the appropriate category where, presently (1982), data may be sparse or absent.

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*Parenthetical numbers in the text are literature citations. See References.

SECTION 2

OCCURRENCE

Volatile organic chemicals are introduced into drinking water by different means. Carbon tetrachloride, for example, is a known contaminant of chlorine produced by the graphite-anode process (2), and disinfection with chlorine produced by this process can be a significant source of carbon tetrachloride in treated drinking water (3). Similarly, other products used in the production and distribution of water are sometimes sources of contaminants. Tetrachloroethylene is leached from polyvinyl-toluene-lined asbestos cement pipe (4), trichloroethylene is present in certain joint compounds used in reservoir liners and covers*, and vinyl chloride has been found as a residual monomer in polyvinyl chloride pipe manufactured before 1977 (5).

Discovering sources of contamination is sometimes complicated by analytical error. In one documented instance, trichloroethylene was thought to have been produced by chlorine used for disinfection, but improved quality control in the laboratory led to the discovery that the material thought to be trichloroethylene was actually a trihalomethane (6).

Because these compounds are volatile, they are seldom detected in concentrations greater than a few micrograms per liter (µg/L) in surface water sources. There is, however, one exception. Surface water vulnerable to wastewater discharges may contain elevated concentrations of organic solvents during periods of ice cover, when volatilization of these solvents is restricted. Seeger's group (7) sampled Ohio River water at Cincinnati during the winter of 1977, when there were almost 800 miles of upstream ice cover, and found atypically high concentrations of compounds such as carbon tetrachloride and tetrachloroethylene.

High concentrations of volatile compounds occur most frequently in ground water. Several possible sources for these contaminants have been suggested (8). Included are industrial discharges (either through spreading on the land or improper disposal at dumps), landfill leachates, septic tank degreasers and similar products from individual households, sewer leaks, accidental spills, water from cleaning and rinsing of tanks and machinery, leaking storage tanks, and treated wastes reintroduced into aquifers as ground water recharge. Solvents can enter an aquifer and be transported great distances because they have little affinity for soils (9-11). Recent sampling (12 through 15, among others) has revealed solvent-contaminated ground waters in several states. The number of water utilities affected is likely to increase when other states examine the organic quality of their ground water.

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*Private communication, Albert E. Sylvia, Commonwealth of Massachusetts, Lawrence Experiment Station, Lawrence, MA (1980).

Contaminated ground water usually contains two or more predominant organic compounds and several identifiable ones of lesser concentration. One reason for this might be related to solvent purity. In the manufacturing of these solvents, the end product depends on the temperature, degree of acidification, and chlorination, so a commercial grade solvent might have varying amounts of several related compounds (Figure 1). Another reason for the presence of a variety of solvents in one location might be biological degradation of a parent compound in the ground (16).

Frequently, within a well field, one well may be uncontaminated, yet a nearby well may contain as high as 2 milligrams per liter (mg/L) of trichloroethylene and several hundred micrograms per liter (μg/L) of tetrachloroethylene and 1,1,1-trichloroethane. However, another well within the same area, but perhaps drawing from a different aquifer may contain a preponderance of 1,1,1-trichloroethane and cis-1,2-dichloroethylene, and have only minimally detectable quantities of trichloroethylene. Finally, the concentrations of contaminants in a well can be variable. For example, at a project in Connecticut (described in detail later in the text), 1,1,1-trichloroethane concentrations ranged from 12 to 214 μg/L over the year-long study. Although contamination from improper pump lubricants or from well drilling aids is not likely to be major, the potential should be recognized.

Sometimes the source of contamination is not obvious. Crane and Freeman (18), for example, reported trichloroethylene and tetrachloroethylene as two of several solvents detected in the effluent from the anion-cation exchange resin used in their laboratory. The source of this contamination was traced to the distribution plant where the resin was sent for regeneration. The ground water used in the regeneration process was contaminated with organic solvents, which then contaminated the resin.

Once an aquifer is contaminated, the water purveyor or other user might either seek an alternative source or provide treatment to reduce contaminant concentrations. Section 3, following, is a compilation of contaminant properties and treatment data, where such data are available.

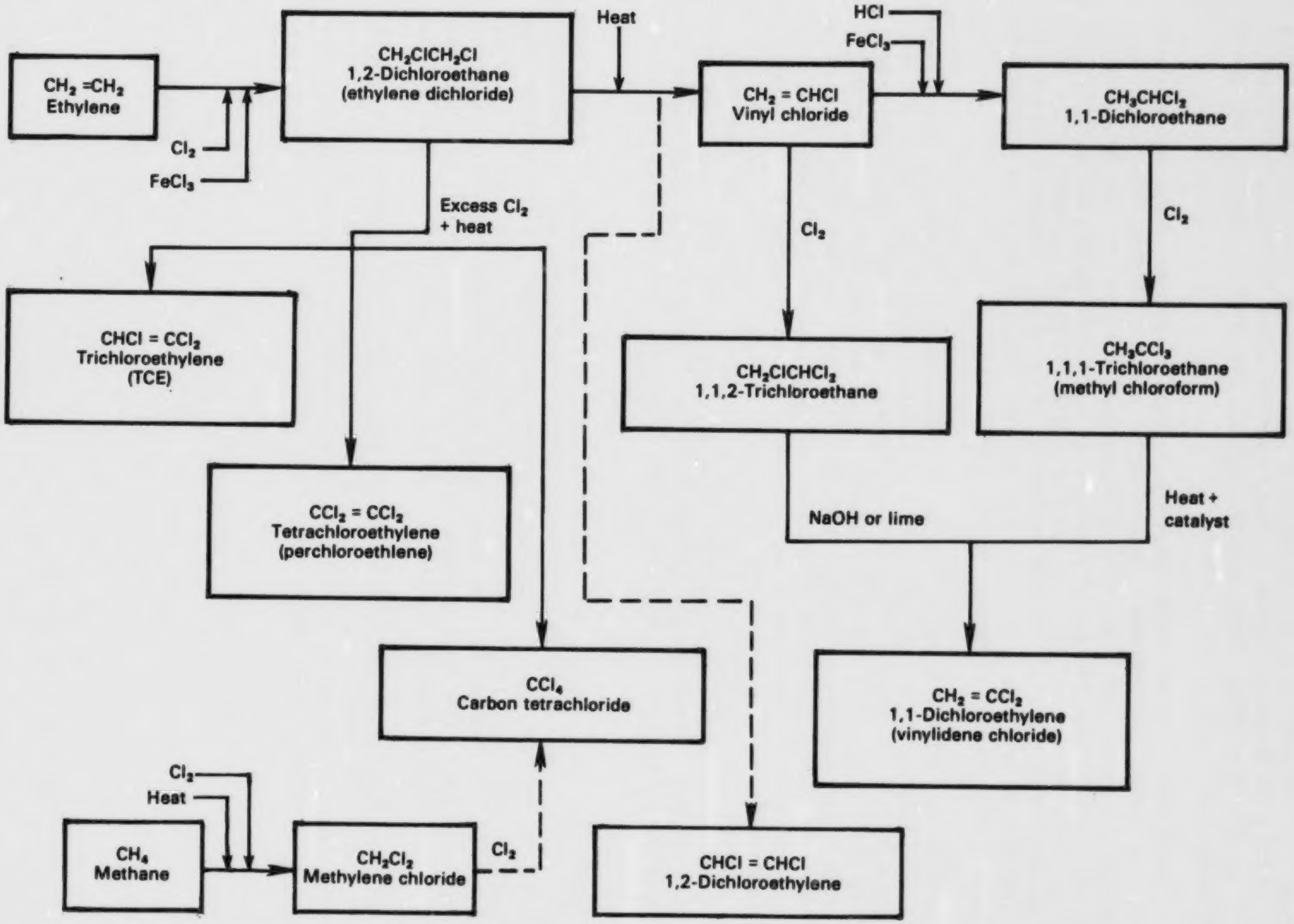

CH₂=CH₂ Ethylene
Cl₂
FeCl₃
CH₂ClCH₂Cl 1,2-Dichloroethane (ethylene dichloride)
Heat
CH₂ = CHCl Vinyl chloride
HCl
FeCl₃
CH₃CHCl₂ 1,1-Dichloroethane
Excess Cl₂ + heat
Cl₂
Cl₂
CHCl = CCl₂ Trichloroethylene (TCE)
CH₂ClCHCl₂ 1,1,2-Trichloroethane
CH₃CCl₃ 1,1,1-Trichloroethane (methyl chloroform)
CCl₂ = CCl₂ Tetrachloroethylene (perchloroethlene)
NaOH or lime
Heat + catalyst
CCl₄ Carbon tetrachloride
CH₂ = CCl₂ 1,1-Dichloroethylene (vinylidene chloride)
Cl₂
Heat
CH₄ Methane
CH₂Cl₂ Methylene chloride
Cl₂
CHCl = CHCl 1,2-Dichloroethylene

Figure 1. Simplified Manufacturing Scheme for Industrial Solvents (17).

SECTION 3

INDIVIDUAL COMPOUND DESCRIPTIONS AND TREATMENT EXPERIENCES

The properties of the sixteen organic chemicals most commonly detected in ground water (1) are summarized in Table 1. Each compound is then discussed separately in an identical format that includes a molecular structure drawing of the compound, other names for the compound, some of its principal uses, and finally, the available treatment information. The term "conventional treatment" includes the processes of chemical coagulation, flocculation, sedimentation, precipitative softening, filtration, and disinfection with chlorine.

TABLE 1. COMPARATIVE DATA FOR SELECTED VOLATILE ORGANIC COMPOUNDS

Parameter	Chloroethylenes					Vinyl Chloride	Chloroethanes	
	tri-	tetra-	cis-1,2-di-	trans-1,2-di	1,1-di-		1,1,1-tri-	1,2-di-
Molecular weight, g/mole	132	166	97	97	97	62	133	99
Density, g/mL	1.46	1.62	1.29	1.26	1.22	0.92	1.34	1.24
Boiling point, °C								
atmospheric	86.7	121	60	48	32	-14	74.1	83.5
azeotropic (w/H_2O)	73.2(19)	88.5(20)	NR	NR	NR	NR	65(19)	71.6(19,20)
Solubility, mg/L	1000(21) 1100(22,23)	150(21,23) 140(22)	3500(22)	6300(22)	40(22)	60(21,22)	4400(21) 5497(23)	8700(21,22)
Vapor pressure, mm Hg (21,22)	74	18.6	206	271	495	2660	100	82
Henry's Law Constant								
$\frac{\text{conc. (air)}}{\text{conc. (water)}}$	0.48(21) 0.49(22)	1.1(21) 1.2(22)	0.31(22)	0.27(21,22)	7.8(21,22)	50(22) 301(21)	0.17(21) 1.2(22)	0.05(21,22)
$\times 10^{-3}$ $\frac{\text{atm-m}^3}{\text{mole}}$ (23)	11.7	28.7	8*	5.2	150	6400(24)	4.92	1.10
Threshold odor concentration, μg/L	500(25,26)	300(25)	NR	NR	NR	NR	NR	2000(25,26)
Parachor (27)	212.8	250	175.6	175.6	175.6	211.3	223.9	186.6
Molar refraction (27)	30.42	35.21	20.71	20.71	20.71	23.85	24.95	21.18

*Calculated from solubility and vapor pressure.
NR - Not reported.

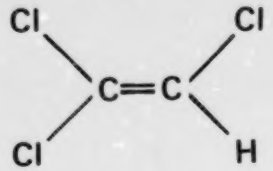
TABLE 1. (Cont'd.)

Parameter	Chloromethanes		Benzene	Chlorobenzenes				
	carbon tetrachloride	methylene chloride		mono-	1,2-di-	1,3-di-	1,4-di-	1,2,4-tri-
Molecular weight, g/mole	154	85	78	113	147	147	147	182
Density, g/mL	1.59	1.33	0.89	1.11	1.31	1.29	1.25	1.45
Boiling point, °C								
atmospheric	76.7	40	80	132	180	173	147	219
azeotropic (w/H_2O)	66.8(19)	38.4(19)	69.4(19)	90.2(28)	NR	NR	NR	NR
Solubility, mg/L	800(21-23)	19,400(22)	1780(29)	448(21)	100(21)	123(21)	79(21)	30(21)
Vapor pressure, mm Hg (21, 22)	91.3(22)	438(22)	95(29)	15(21)	1.0(21)	2.0(21)	1.0(21)	0.29(23)
Henry's Law Constant								
$\frac{\text{conc. (air)}}{\text{conc. (water)}}$	1.2(21,22)	0.10(22) 0.12(21)	0.22(21)	0.19(21)	0.08(21)	0.13(21)	0.10(21)	0.06*
$\times 10^3$ $\frac{\text{atm-m}^3}{\text{mole}}$ (23)	30.2	3.19	5.55	3.93	1.94	1.94	1.94	1.42
Threshold odor concentration, μg/L	(30)	NR	31,300(25)	NR	NR	NR	NR	NR
Parachor (27)	220.0	146.6	207.1	244.1	280.5	280.5	280.5	317.2
Molar refraction (27)	26.30	16.56	26.2	31.2	36.1	36.1	36.1	40.9

*Calculated from solubility and vapor pressure.
†Test inconclusive. Two of seven panel members reported detection at a CCl_4 concentration of 400 μg/L.
NR - Not reported.

TRICHLOROETHYLENE*

Structure



Other Names (31-33)

TCE; 1,1,2-trichloroethylene; 1,2,2-trichloroethylene; trichloroethene; acetylene trichloride; ethinyl trichloride; ethylene trichloride; Triclene; Trielene; Trilene; Trichloran; Trichloren; Algylen; Trimar; Triline; Tri; Trethylene; Westrosol; Chlorilen; Gemalgene; Germalgene; Benzinol; 1,1-dichloro-2-chloroethylene; Blacsolv; Blancosolv; Cecolene; 1-chloro- 2,2-dichloroethylene; Chlorylen; Circosolv; Crawhaspol; Dow-tri; Dukeron; Fleck-flip; Flock-flip; Lanadin; Lethurin; Nalco 4546; Nialk; Perm-a-clor; Petzinol; Philex; Triad; Trial; Trisol; Anamenth; Chlorylen; Densinfluat; Fluate; Narcogen; Narkosoid; Threthylen; Threthylene; Trilen

Trichloroethylene is commercially produced by chlorinating ethylene ($CH_2 = CH_2$) or acetylene ($CH \equiv CH$). Its use is declining because of stringent regulations; however, it has been a common ingredient in many household products (spot removers, rug cleaners, air fresheners), dry cleaning agents, industrial metal cleaners and polishers, refrigerants, and even anesthetics (17, 29, 34). Its ubiquitous use is perhaps why trichloroethylene is the organic contaminant most frequently encountered in ground water.

Conventional Treatment

Two studies were found in the literature in which trichloroethylene was identified and measured before and after conventional water treatment. In both studies, the trichloroethylene concentration in the source was lower than 1 µg/L, but no significant removals were observed through the treatment plant (7, 35).

Aeration

Pilot scale laboratory and field aeration studies were conducted using a 4-cm (1.5-in) diameter glass column, approximately 1.2 m (4 ft) long, with a fritted glass diffuser in the bottom. Water was introduced at the top of the column to give a counter-current flow. In the laboratory, trichloroethylene was added to Cincinnati, Ohio, tap water to give concentrations of approximately 100 to 1000 µg/L. The water was aerated at varying temperatures. Trichloroethylene was stripped from the water at an efficiency of from 70 to 92 percent using an air-to-water ratio (volume-to-volume) of 4:1, and a contact time of 10 minutes (Table 2). An identical aerator consistently removed over 80 percent of the trichloroethylene from a contaminated

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*See Table 1, page 6, for properties.

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TABLE 2. REMOVAL OF TRICHLOROETHYLENE FROM DRINKING WATER BY DIFFUSED-AIR AERATION

Location of study	Average influent concentration, µg/L	Average effluent concentration, µg/L Air-to-water ratios 1:1	2:1	3:1	4:1	8:1	16:1	20:1	Remarks
"Spiked" Cincinnati, Ohio tap water	1064	796	614	508	319	53			4-cm (1.5-in) diam. counter-current flow glass column with activated carbon filtered air; 10 min. contact time. Water temperature 6-16°C. Depth = 0.8m.
	397	223	273	102	82	22	<1	<1	
	241	136	110	61	53	8	2	3	
	110	40	28	18	9	3	<1	<1	
	73	22	14	8	6	1	<1	<1	
Contaminated well in New Jersey	3				<1				

Location of study	Average influent concentration, µg/L	Air-to-water ratios 5:1	10:1	15:1	20:1	Remarks
Contaminated well on Long Island (36)	112	72^a	48^c			$0.4\ m^3$ ($16\ ft^3$) rectangular tank with 4 diffusers. Depth = 0.6m a. 10-min contact time b. 15-min contact time
	64		$27^{a,d}$			
	118			40^e 40^b		
	122				33^f 44^b	27-cm (10.5-in) diameter column. Depth = 0.6m c. 5-min contact time d. 10-min contact time e. 15-min contact time f. 20-min contact time

Location of study	Average influent concentration, µg/L	Air-to-water ratios 5:1	15:1	20:1	30:1	Remarks
Contaminated well on Long Island (37)	180	56				76-cm (30-in) diameter 3-m (10-ft) deep glass column with 5 diffusers; 10-min contact time.
	218		45			
	210			35		
	225				22	

Note: Blank spaces indicate no tests conducted.

well in New Jersey with a mean influent concentration of 3.3 μg/L.

Nebolsine Kohlman Ruggiero Engineers (NKRE) (36) also evaluated diffused-air aeration on a pilot scale at a well site on Long Island, New York (see Table 2). They used a rectangular aeration tank [0.6m x 1.2m x 0.6m deep (16 ft^3)] having four diffusers and a 27-cm (10.5-in) diameter Plexiglas column having a single diffuser and observed TCE removal efficiency. Retention times ranged from 5 to 20 minutes and air-to-water ratios from 5:1 to 20:1. The highest removal efficiency was 73 percent. In a follow-up study (37) that employed a 76-cm (30-in) diameter column, 3m (10 ft) in length and with five diffusers, the efficiency of removal ranged from 69 percent to 90 percent, with air-to-water ratios from 5:1 to 30:1. The trichloroethylene concentration in the unaerated water ranged from 132 to 313 μg/L.

Joyce (38) reported concentrations of trichloroethylene ranging from 4.5 to 22 μg/L at Smyrna, Delaware, after water containing 20 to 70 μg/L trichloroethylene was passed through an induced-draft, redwood slat aerator. Also, the advanced waste treatment research conducted in southern California at Water Factory 21, although not focused directly on drinking water, showed that trichloroethylene concentrations of approximately 1 to 2 μg/L were removed with 98 percent effectiveness. This was accomplished through an ammonia-stripping tower with an air-to-water ratio of approximately 3000 to 1 (when the fan was operating). Similar removal efficiencies for volatile organic chemicals were observed on wastewater passed through a polyethylene-packed decarbonator operating with an air-to-water ratio of about 22 to 1 (24,39).

Adsorption

Dobbs and Cohen (40) developed an adsorption isotherm for trichloroethylene in distilled water by using pulverized Filtrasorb® 300* activated carbon. The Drinking Water Research Division, USEPA, followed the same procedure but used both Filtrasorb® 300 and Witcarb 950† pulverized carbons. These data are illustrated in Figure 2 as Freundlich isotherms. With a trichloroethylene concentration of 100 μg/L, the capacity predicted from these isotherms ranges from 7 to 10 mg trichloroethylene per gram of activated carbon (mg/g). Other than isotherm data, little information has been reported on the effects of powdered activated carbon for removing high concentrations of this contaminant. Singley's group (41) observed a 50 percent reduction in trichloroethylene concentrations (from 1.5 to 0.7 μg/L) at the Sunny Isles Water Treatment Plant, North Miami Beach, Florida. The reduction was accomplished with a powdered activated carbon dosage of 7 mg/L.

A great deal more adsorption data have been developed for granular adsorbents. In the summer and fall of 1977, the Drinking Water Research Division installed pilot scale adsorption columns of 4 cm (1.5 in) diameter

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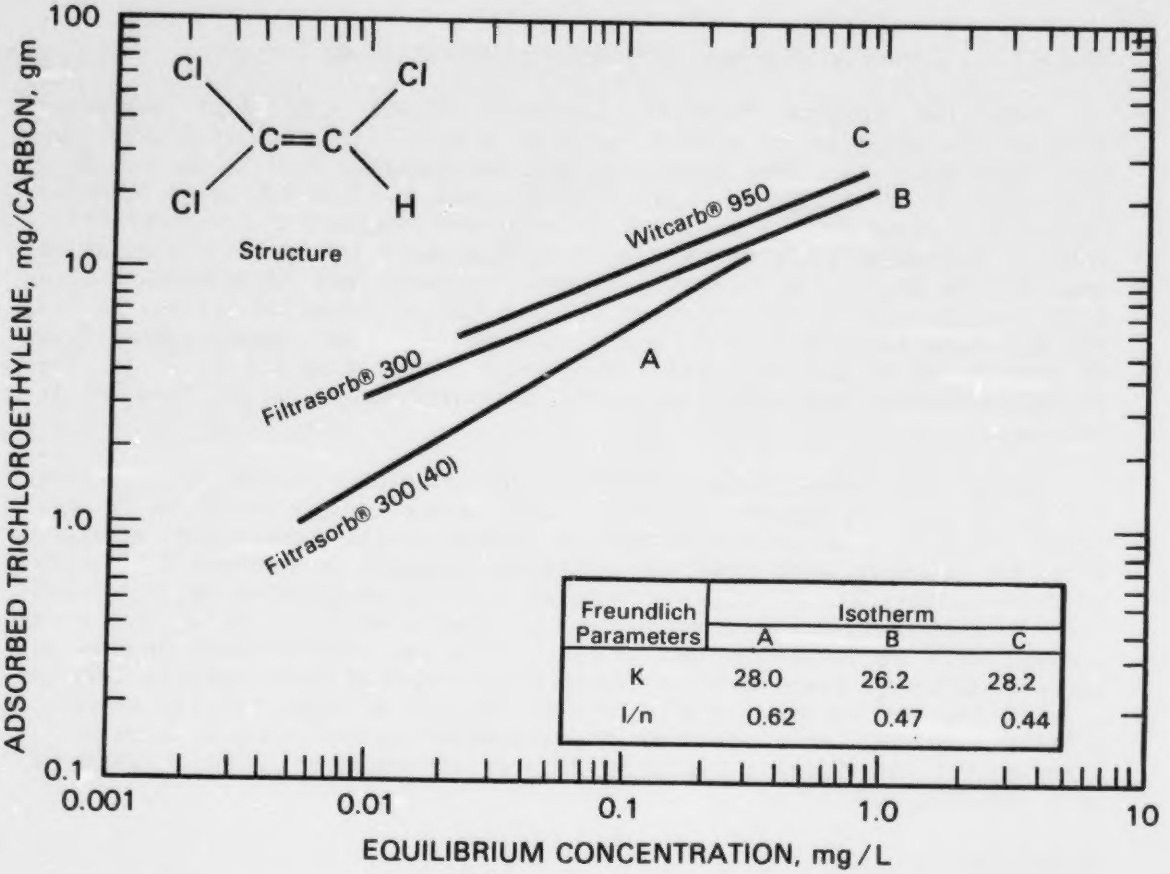
*Calgon Corporation, Pittsburgh, PA.
†Witco, Inc., New York, N.Y.



Freundlich Parameters	Isotherm A	Isotherm B	Isotherm C
K	28.0	26.2	28.2
l/n	0.62	0.47	0.44

Figure 2. Isotherms for Trichloroethylene Adsorption on Activated Carbon.

and 80 cm (31 in) media depth near contaminated wells at water utilities in Connecticut and New Hampshire. At the Connecticut installation, an industrial waste lagoon was thought to have contaminated the well field. The affected waterworks had just completed two years of pumping the contaminated well to waste, yet volatile organics were still present. At both locations, granular activated carbon (Filtrasorb® 400) and a synthetic resin, (Ambersorb® XE-340*, were exposed to the contaminated water.

In the New Hampshire study, trichloroethylene was the predominant contaminant, and concentrations ranged from 120 to 276 μg/L. Unfortunately, after 18 weeks, the test column became clogged with what appeared to be precipitated iron. When cleaning was attempted, the contaminant wavefront was disrupted; the study was ended after 23 weeks (Figure 3). In the Connecticut study, trichloroethylene was one of the lesser contaminants, and its concentrations ranged from less than 1 μg/L to 10 μg/L. The test columns were sampled weekly for one year, were then allowed to run continuously for one year, and were finally resampled. While trichloroethylene was removed to below detection (0.1 μg/L) for the first year, the granular activated carbon was exhausted after two years. This means the adsorption capacity was between 61,570 and 123,340 bed volumes, or 0.7 to 1.4 mg/g. The resin, however, was still removing trichloroethylene to "below detection" at the time (Figure 3).

In laboratory studies with trichloroethylene concentrations at the 2 mg/L level, Neely and Isacoff (42) reported the equilibrium capacity on XE-340 was 84 mg/g (25,200 m^3/m^3). A pilot scale field study on Long Island (37) further evaluated the XE-340 resin. In this project, 10-cm (4-in) diameter columns with different depths of resin (to vary contact times) were examined. Trichloroethylene capacity to breakthrough† on the XE-340 resin was approximately 12 mg/g (29,500 m^3/m^3). The influent trichloroethylene concentrations ranged from 132 to 313 μg/L, and the resin depths varied from 0.3 to 1.2 m, giving contact times of 2 to 8 minutes.

In Montgomery County, Pennsylvania, some homes with private wells contaminated with trichloroethylene have used Culligan adsorption units. These home treatment devices contain approximately 40 kg (87 lbs) of granular activated carbon and reportedly maintain effluent trichloroethylene concentrations below 5 μg/L for several months (43). Information on the effectiveness of other home treatment units to remove trichloroethylene, particularly the small, low flow cartridges containing only a few grams of activated carbon, is not yet available.

Boiling

Boiling is sometimes suggested as a means of ridding drinking water of

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*Rohm and Haas Co., Philadelphia, PA.

†Unless otherwise indicated, breakthrough is the length of service when at least 0.1 μg/L of the contaminant is consistently detected in the effluent from the adsorbent. Length of service is expressed in both time and bed volumes (m^3 water/m^3 adsorbent).

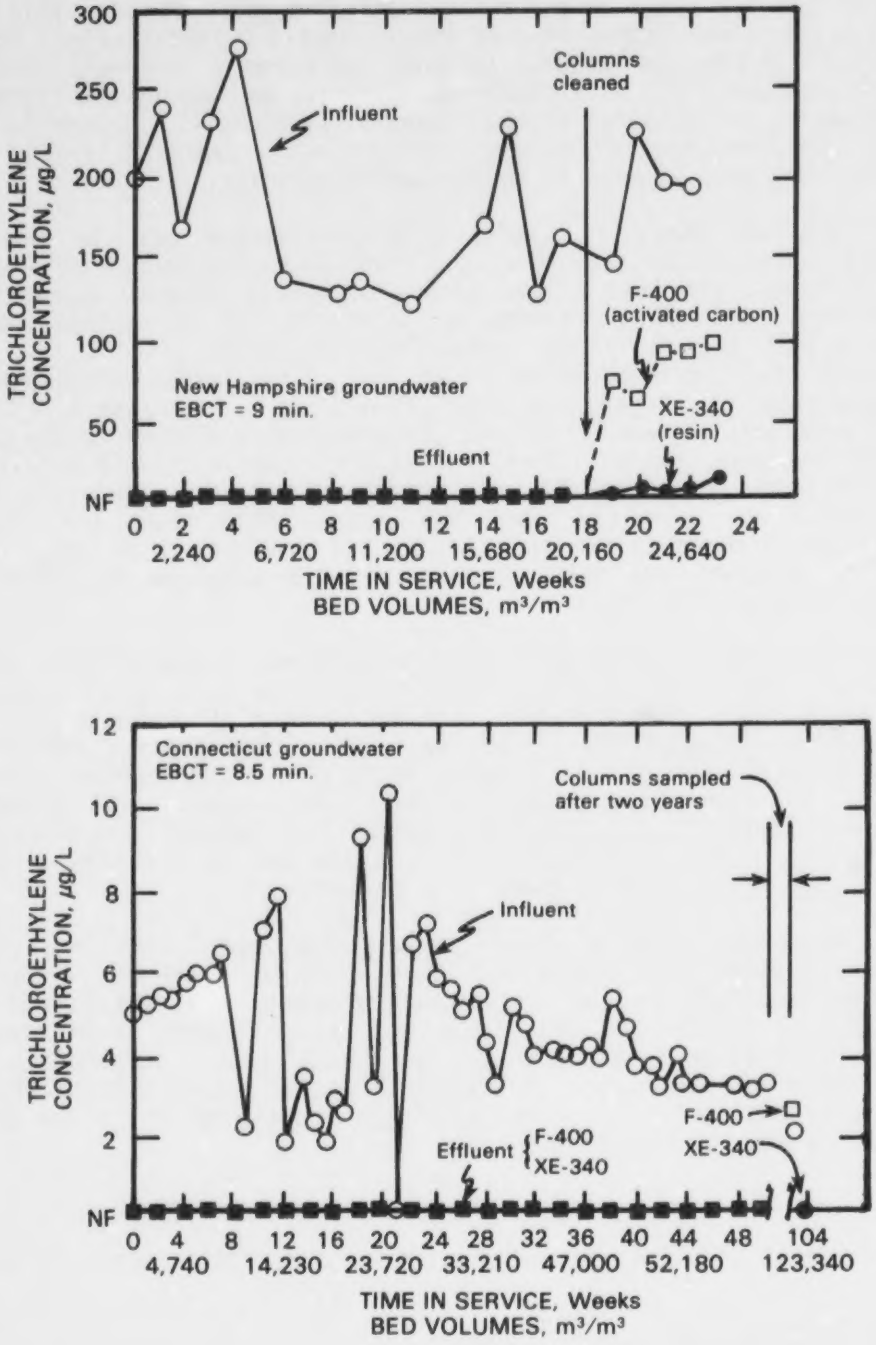


Figure 3. Removal of Trichloroethylene by Adsorption on Granular Activated Carbon and Polymeric Resin.

volatile organics. Table 3 shows the results from four studies conducted by the USEPA in which 12 water samples were boiled for varying times. Because boiling is not a standardized procedure, conditions are likely to vary between households. Lataille (44) for example, noted the importance of water depth to boiling efficiency. She found trichloroethylene was more efficiently removed by boiling from a vessel containing 2 to 5 cm (1 to 2 in) of water than from one having greater water depths (Table 3).

TABLE 3. REMOVAL OF TRICHLOROETHYLENE FROM DRINKING WATER BY BOILING

Time of boiling, minutes	Trichloroethylene concentration, μg/L									
	A		B		C		D			
0 (before heating)	142	1262	137	1107	176	1830	730	1460	2920	2000
1	25	237	45	589	28	279				
2	17	186	44	389	20	110				
3	12	136	35	261	20	57				
5	5	65	23	118	11	20	12	17	194	6*, 29†, 500‡

A - Spiked tap water from Cincinnati, Ohio

B - Spiked distilled water

C - Contaminated well water from Pennsylvania

D - Spiked tap water from Lexington, Massachusetts

* Water depth = 2 cm (1 in)

† Water depth = 5 cm (2 in)

‡ Water depth = 11 cm (5 in)

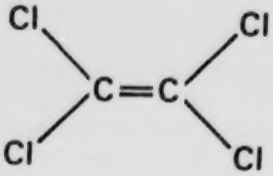
Studies A-C by Drinking Water Research Division, USEPA, Cincinnati, Ohio. Water depth approximately 10 cm (4 in).

Study D by USEPA Region I, Surveillance and Analysis Laboratory, Lexington, Massachusetts (44).

Note: Blank spaces indicate no tests conducted.

TETRACHLOROETHYLENE*

Structure



Other Names (31-33)

PCE; perchloroethylene; 1,1,2,2-tetrachloroethylene; tetrachloroethene; Ankilostin; carbon bichloride; carbon dichloride; Didakene; ENT-1860; ethylene tetrachloride; NCl-C04580; Nema; Perawin; Perc; Perclene; PerSec; Tetrales; Tetracap; Tetropil; Antisal; Fedan-Un; Tetlen; Tetraguer; Tetraleno

Tetrachloroethylene is commercially produced by chlorinating acetylene ($CH \equiv CH$) or 1,2-dichloroethane (CH_2ClCH_2Cl), also known as ethylene dichloride. This solvent is widely used in dry cleaning, textile dyeing, metal degreasing, and in the synthesis of fluorocarbons (17, 34). Tetrachloroethylene has been used to apply polyvinyl-toluene liners to asbestos-cement pipe. This solvent leaches into finished drinking water from newly laid pipe, as well as from pipe that has been installed for several years (4). Tetrachloroethylene concentrations from this source range from a few micrograms per liter to several milligrams per liter, the higher concentrations coming from dead-ends, where water flow is not continuous. Specifications placed on new pipe can alleviate this source of contamination, but treatment for existing polyvinyl-toluene lined pipe in the ground is a problem that needs attention.

Conventional Treatment

Although tetrachloroethylene is mainly a groundwater contaminant, it has been found in low, measurable concentrations in some surface waters. In one instance, tetrachloroethylene was monitored before and after coagulation, sedimentation, and filtration, and these processes, it was shown, were ineffective for lowering its concentration (7).

Oxidation

Oxidation by ozone has been suggested, and, though Glaze (45) has shown that ozonation can reduce tetrachloroethylene concentrations, optimum conditions and subsequent by-products are unknown. Hoigne and Baden (46) achieved a 40 percent reduction in tetrachloroethylene concentration (initial concentration 500 μg/L) in lake water with an ozone dose of 3.3 mg/L.

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*See Table 1, page 6, for properties.

Aeration

Diffused-air aeration is effective for stripping tetrachloroethylene from water. Laboratory studies have found that 30 to 60 percent of tetrachloroethylene can be removed at an air-to-water ratio of 1:1. Laboratory and pilot scale field studies have shown at least 95 percent removal of tetrachloroethylene at higher air-to-water ratios (Table 4). McCarty's group (24) reported 94 percent removal of tetrachloroethylene (average influent concentration of 2.8 μg/L) in ammonia stripping towers fed with highly treated wastewater.

Adsorption

Adsorption isotherms for tetrachloroethylene in distilled water are presented in Figure 4. If a tetrachloroethylene concentration of 100 μg/L is assumed, the range of equilibrium capacities from these isotherms would be 14 to 69 mg/g.

Adsorption tests using granular material on a pilot scale were conducted in Rhode Island by the Drinking Water Research Division during the summer of 1977. A portion of a drinking water distribution system had become contaminated with 600 μg/L to 2500 μg/L of tetrachloroethylene from polyvinyl-toluene lined asbestos cement pipe (4). Two different adsorbents were examined with 4-cm (1.5-in) diameter glass columns. One test column contained Filtrasorb® 400 granular activated carbon, and a parallel column, Ambersorb® XE-340 synthetic resin. Both columns had an 8.5-minute empty bed contact time. The granular activated carbon maintained an effluent concentration of tetrachloroethylene below 0.1 μg/L for 11 weeks, giving a breakthrough loading of 46.7 mg/g (12,900 m^3/m^3). Because of inclement weather, the study was stopped after 20 weeks. At that time the resin was passing an average of 0.4 μg/L tetrachloroethylene (Table 5), giving an empirical loading to breakthrough of 45.6 mg/g (18,800 m^3/m^3). Although the resin was similar to the activated carbon in loading to breakthrough, it exhibited a relatively flat breakthrough curve. This suggests that the rate of contaminant movement through this resin is slow, relative to the wavefront movement through activated carbon.

One of the objectives of a USEPA study in New Jersey was to examine the effectiveness of adsorption. A contaminated well was intermittently pumped into a stainless steel tank having a floating lid. The water was then pumped to adsorption columns and an aerator (Figure 5). In the non-aerated water, tetrachloroethylene concentrations ranging from 60 to 205 μg/L were reduced to less than 0.1 μg/L throughout the study (58 weeks) by the granular activated carbon (18-minute empty bed contact time), giving a loading to breakthrough of >6 mg/g (> 32,000 m^3/m^3). Similarly, after 58 weeks, resin column effluent concentrations were <0.1 μg/L which yields a loading of >17.7 mg/g (>117,000 m^3/m^3). The tetrachloroethylene concentrations remaining after aeration (see Table 4) were also removed to below detection by both the resin and activated carbon.

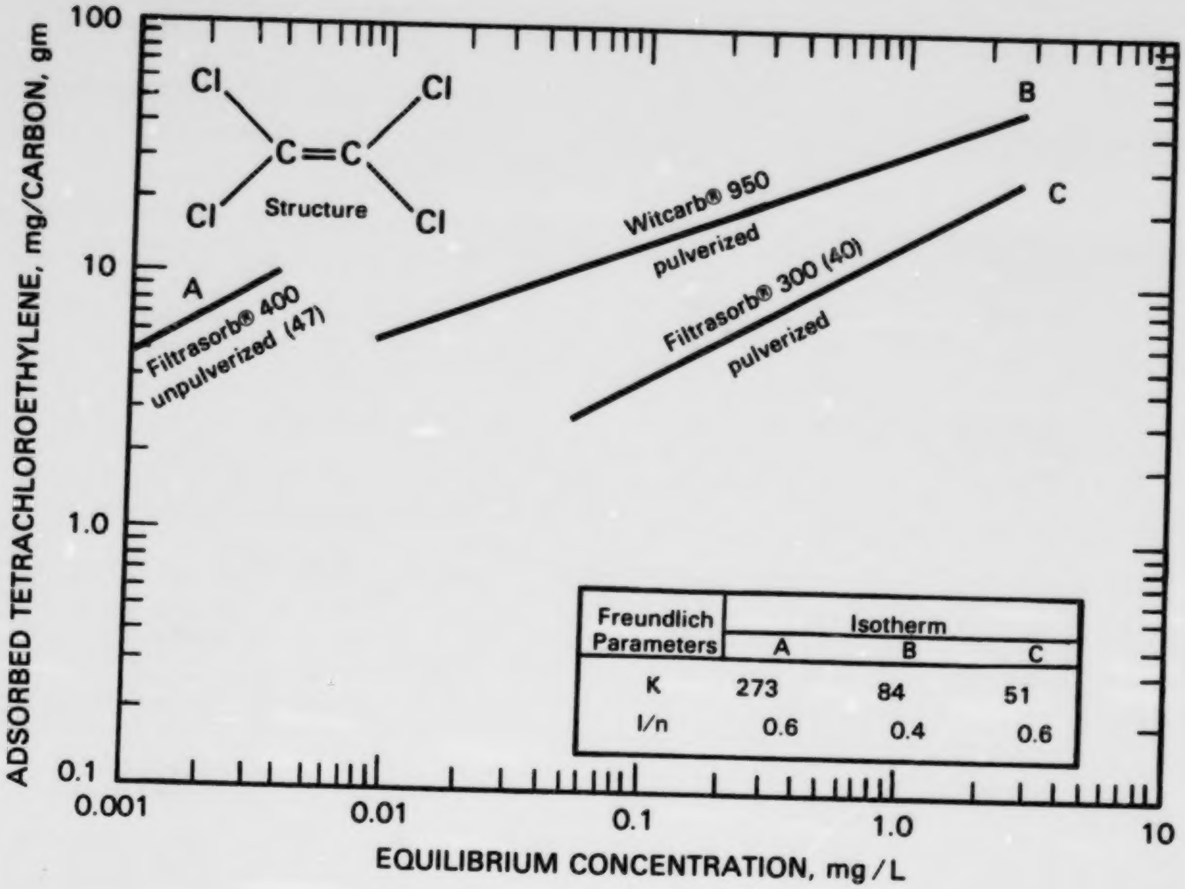
TABLE 4. REMOVAL OF TETRACHLOROETHYLENE FROM DRINKING WATER BY DIFFUSED-AIR AERATION

Location of study	Average influent concentration, μg/L	Average effluent concentration, μg/L Air-to-water ratios 1:1	2:1	3:1	4:1	8:1	16:1	20:1	Remarks
"Spiked" Cincinnati, Ohio tap water	1025	698	416	304	156	16			4-cm (1.5-in) diameter glass column, 10-min. contact time. Depth = 0.8m
	636	161	177	46	34	8	<1	<1	
	338	139	103	47	34	4	1	2	
	114	32	17	7	4	<1	<1	<1	
	107	32	17	7	4	<1	<1	<1	
	17	3	2	1	1	<1	<1	<1	
Contaminated well in New Jersey	92				9				

		Air-to-water ratios 5:1	10:1	15:1	20:1	
Contaminated well on Long Island (36)	55	33^{a}	17^{c}			0.4 m^3 (16 ft^3) rectangular tank with 4 diffusers. Depth = 0.6m a. 10-min contact time b. 15-min contact time 27-cm (10.5-in) diameter column. Depth = 1.7m c. 5-min contact time d. 10-min contact time e. 20-min contact time
	27		$8^{d,a}$			
	46			10^{d} 14^{b}		
	65				11^{e} 19^{b}	

		Air-to-water ratios 5:1	15:1	20:1	30:1	
Contaminated well on Long Island (37)	101	25				76-cm (30-in) diameter, 3-m (10-ft) deep glass column with 5 diffusers, 10-min contact time.
	92		15			
	52			4		
	50				3	

Note: Blank spaces indicate no tests conducted.



Freundlich Parameters	Isotherm A	Isotherm B	Isotherm C
K	273	84	51
l/n	0.6	0.4	0.6

Figure 4. Isotherms for Tetrachloroethylene Adsorption on Activated Carbon.

TABLE 5. REMOVAL OF TETRACHLOROETHYLENE FROM DRINKING WATER BY ADSORPTION*

Time in operation, weeks (bed volumes m^3/m^3)	Average concentration, µg/L		
		Effluent	
	Influent	Filtrasorb® 400 activated carbon	Ambersorb® XE-340 resin
4 (4700)	1367	<0.1	<0.1
8 (9400)	1984	<0.1	0.1
12 (14,100)	1950	0.1	<0.1
16 (18,800)	906	0.2	0.2
20 (23,500)	825	2.8	0.4

*Study by USEPA in Rhode Island. Empty bed contact time = 8.5 min. Approach velocity = 5m/hr (2 gal/min-ft^2).

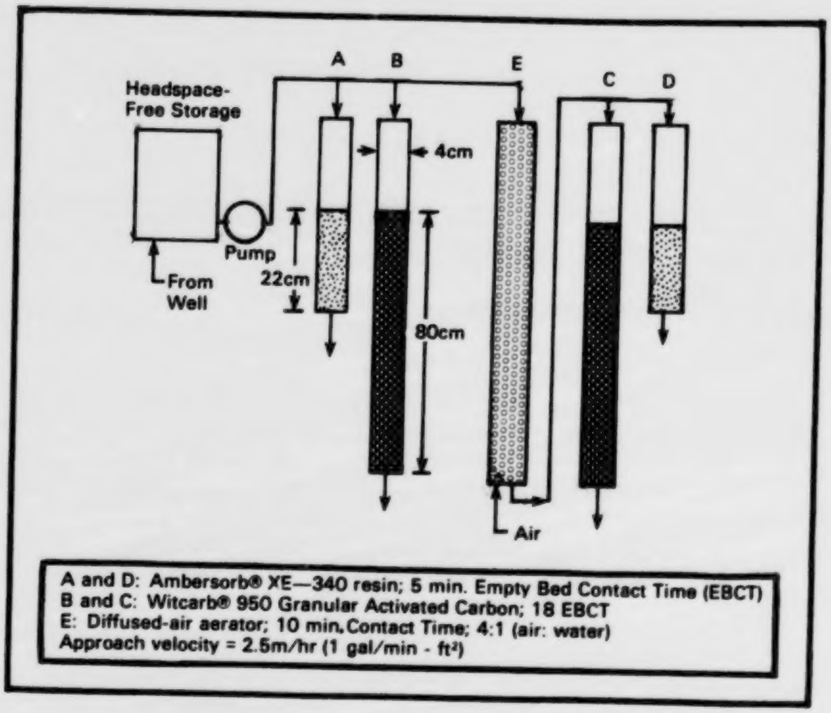

Headspace-Free Storage
From Well
Pump
A
B
E
C
D
4cm
22cm
80cm
Air
A and D: Ambersorb® XE—340 resin; 5 min. Empty Bed Contact Time (EBCT)
B and C: Witcarb® 950 Granular Activated Carbon; 18 EBCT
E: Diffused-air aerator; 10 min. Contact Time; 4:1 (air: water)
Approach velocity = 2.5m/hr (1 gal/min - ft²)

Figure 5. Illustration of USEPA-DWRD Pilot Scale Treatment Used at Contaminated Well Site in New Jersey.

Boiling

The boiling point of tetrachloroethylene is 121°C, but it forms a negative azeotrope with water and boils below 100°C (20). Table 6 shows the results of four separate boiling experiments. Although different quality waters were used, only 1 to 2 percent of the initial concentration of tetrachloroethylene remained after 3 minutes of vigorous boiling in each experiment.

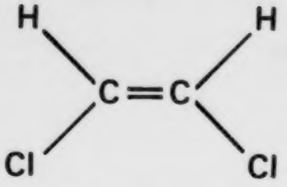
TABLE 6. REMOVAL OF TETRACHLOROETHYLENE FROM WATER BY BOILING

Time of boiling, minutes	Tetrachloroethylene concentration, µg/L			
	A	B	C	
0 (Before heating)	300	298	120	9
1	14	29	11	2
2	6	14	7	< 1
3	3	5	3	< 1
5	2	2	< 1	< 1
10	< 1	< 1	< 1	< 1

A - Spiked Cincinnati, Ohio, tap water
B - Spiked distilled water
C - Contaminated well water from Pennsylvania

CIS-1,2-DICHLOROETHYLENE*

Structure



Other Names (31, 32)

cis-acetylene dichloride; cis-1,2-dichloroethane; NCl-C51581

This isomer of dichloroethylene is used as a solvent and a fermentation retardant (31).

Conventional Treatment

Wood's group (48) has indicated that, in Miami, Florida, ground water, the cis-1,2-dichloroethylene concentraton was 25 µg/L and that precipitative softening and filtration ineffectively removed it.

Aeration

NKRE, an engineering firm, removed, by aeration from well water, 58 percent of an 18-µg/L to 118-µg/L (average 58 µg/L) concentration of cis-1,2-dichloroethylene at an air-to-water ratio of 5:1. The removal could be increased to 85 percent with a 30:1 air-to-water ratio (37). In a Drinking Water Research Division aeration study in New Jersey, 80 percent removal of this contaminant was observed at an air-to-water ratio of 4:1 and 10 minutes contact time. The diffused-air aeration devices used in both the above studies are described in Table 2.

Adsorption

USEPA developed isotherms for the adsorption of cis-1,2-dichloroethylene in distilled water on pulverized Witcarb® 950 and pulverized Filtrasorb® 300. The estimated adsorption capacities are 2.7 and 1.4 mg/g, respectively, for the solvent at an equilibrium concentration of 100 µg/L (Figure 6). At a utility in New Hampshire (see pages 11 and 13 for description), the cis-1,2-dichloroethylene averaged 6 µg/L in the water applied to the pilot scale adsorber (Figure 7), and the capacity for the activated carbon at exhaustion was 0.2 mg/g. At a site in Connecticut (also described on pages 11 and 13), the average concentration of cis-1,2-dichloroethylene was 2 µg/L, and the adsorption capacity on activated carbon was 0.1 mg/g. Companion adsorbers containing Ambersorb® XE-340 were also monitored at these two New England sites. The resin maintained an effluent concentration of cis-1,2-dichloroethylene below detection for the duration of the New Hampshire study (20 weeks), and for more than one year, but less than 2

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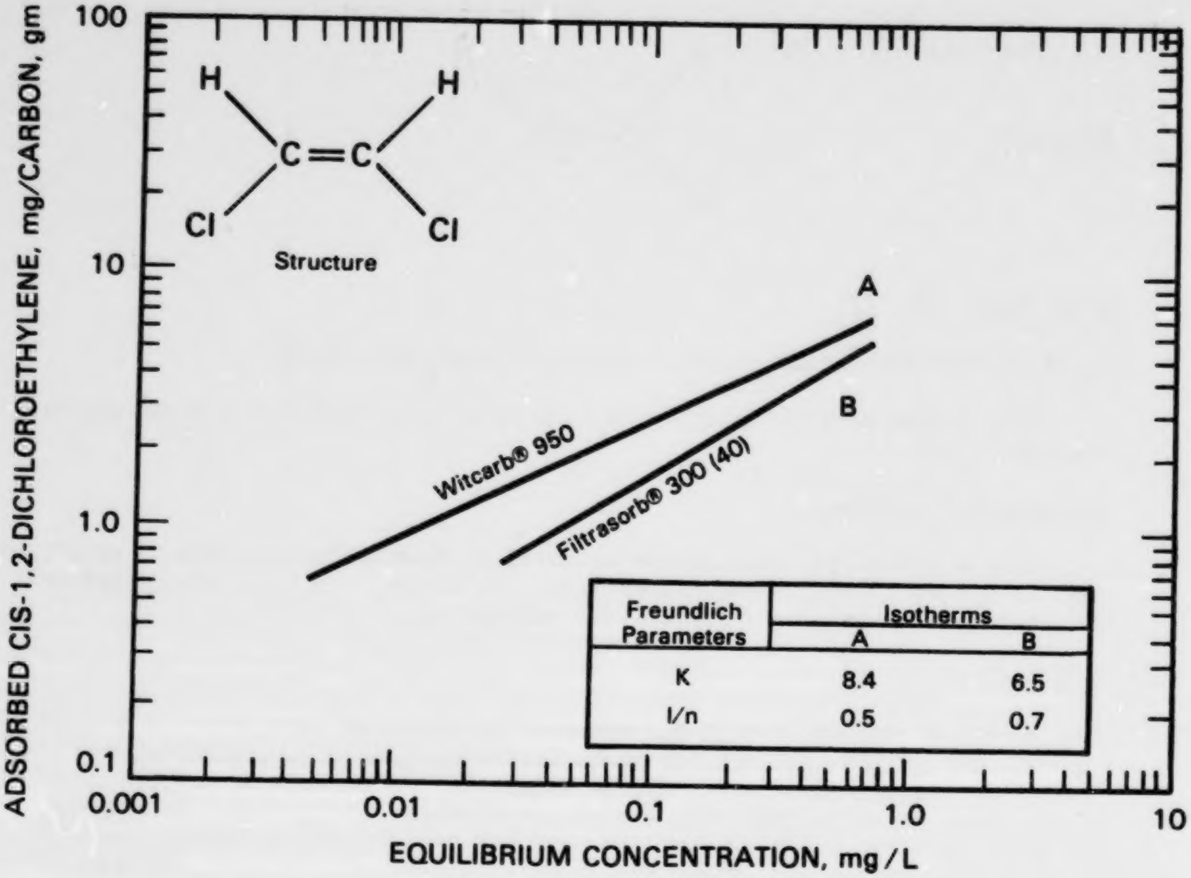
*See Table 1, page 6, for properties.



Freundlich Parameters	Isotherms A	Isotherms B
K	8.4	6.5
I/n	0.5	0.7

Figure 6. Isotherms for Cis-1,2-Dichloroethylene Adsorption on Activated Carbon.

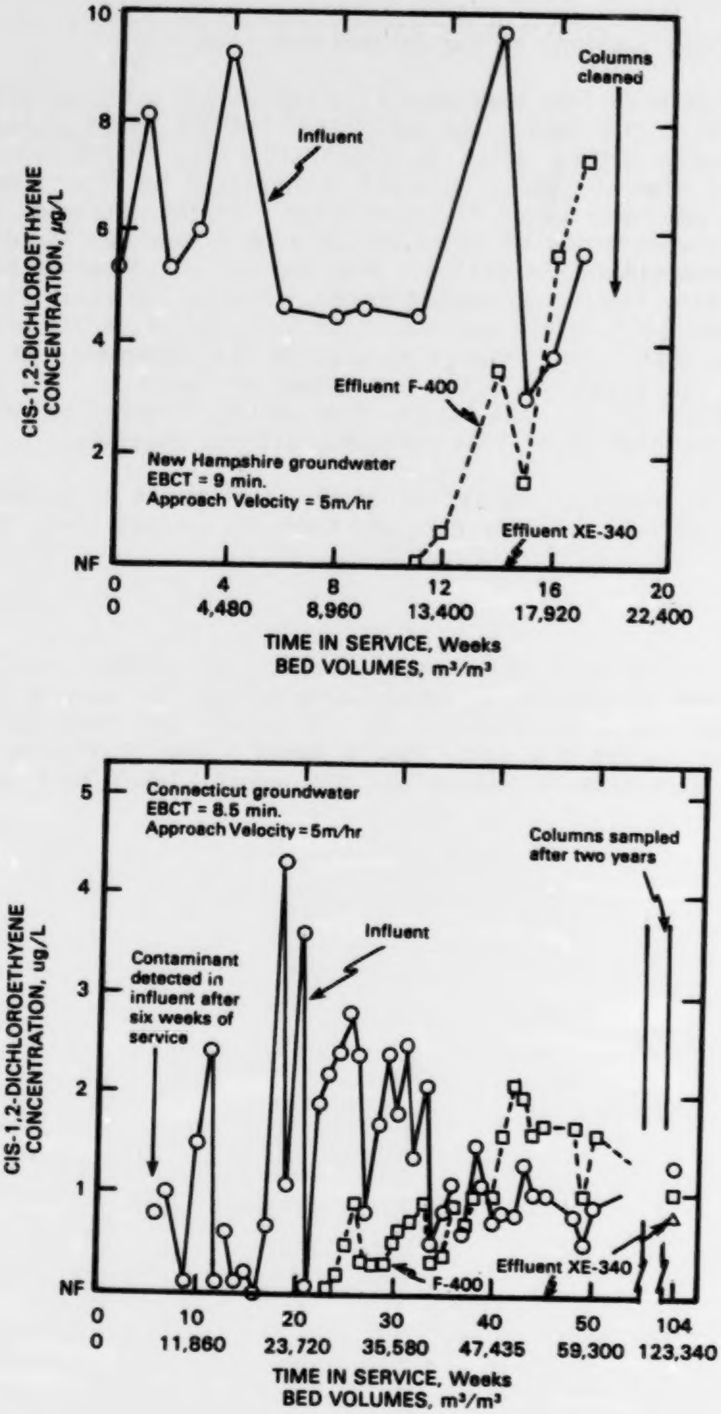


Figure 7. Removal of Cis-1,2-Dichloroethylene by Adsorption on Granular Activated Carbon and Polymeric Resin.

years (>5.4 mg/g loading) at the Connecticut site.

Wood and DeMarco (48) evaluated Filtrasorb® 400 granular activated carbon, Ambersorb® XE-340 resin, and Amberlite® IRA-904 anion exchange resin on the organic-laden ground water in Miami, Florida. Pilot scale adsorbers [2.5-cm (1-in) diameter glass columns] were placed on flow streams of raw, lime-softened and chlorinated filtered water. In the untreated (raw) water, the average concentration of cis-1,2-dichloroethylene was 25 µg/L, and this solvent was detected in the effluent from the activated carbon between weeks 2 and 3 (0.3 mg/g loading to breakthrough). The XE-340 resin lasted approximately 9 weeks (0.7 mg/g), and the anion exchange resin did not remove any of the contaminant. The effects of placing the adsorbents at other locations within the treatment plant are shown in Table 7. The XE-340 resin performed better on the raw water than on the treated water, which may indicate how the high pH of lime softening affects capacity.

NKRE (37) reported nearly identical loadings to breakthrough and to exhaustion on XE-340 resin for a 2- and 4-minute contact time; this is shown in Table 7.

Boiling

Two samples of well water from Pennsylvania, having cis-1,2-dichloroethylene as one of the contaminants, were boiled for varying times by the Drinking Water Research Division in Cincinnati and then analyzed. The results, given in Table 8, show that between 5 and 10 minutes of vigorous boiling were necessary to reduce the contaminant level to 5 µg/L or less.

TABLE 7. REMOVAL OF CIS-1,2-DICHLOROETHYLENE BY ADSORPTION

				Service to breakthrough*		
Adsorbent	Average influent concentration, µg/L	Bed depth, m (ft)	Empty bed contact time, minutes	Time, days	Bed volumes, m^3/m^3	Loading, mg/g
		[Miami, FL (48)]				
Filtrasorb® 400 on raw water	25	0.8 (2.5)	6	18	4300	0.3
Filtrasorb® 400 on filtered water	18	0.8 (2.5)	6	18	4300	0.2
		1.5 (5)	12	59	7100	0.3
		2.3 (7.5)	18	101	8000	0.4
		3.1 (10)	25	>122	>7000	>0.3
Ambersorb® XE-340 on raw water	25	0.8 (2.5)	6	60	14,400	0.7
Ambersorb® XE-340 on lime-softened water	22	0.8 (2.5)	6	30	7200	0.3
Ambersorb® XE-340 on filtered water	16	0.8 (2.5)	6	48	11,500	0.4
Amberlite® IRA-904	27	0.8 (2.5)	6	Not effective		
		1.5 (5)	12	Not effective		
		[Glen Cove, NY (37)]				
Ambersorb® XE-340	40	0.3 (1)	2	48	37,200	1.7
		0.6 (2)	4	102	39,500	1.9
				Service to exhaustion†		
Ambersorb® XE-340	50	0.3 (1)	2	67	51,900	4.2
	45	0.6 (2)	4	153	59,400	4.4

*0.1 µg/L or more in effluent
†Effluent = influent

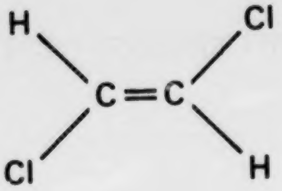
TABLE 8. REMOVAL OF CIS-1,2-DICHLOROETHYLENE FROM WATER* BY BOILING

Time of boiling, minutes	Concentration, μg/L	
	Sample 1	Sample 2
0 (before heating)	739	153
1	168	43
2	51	34
3	31	34
5	14	20
10	<1	5

*Contaminated well water from Pennsylvania. Study by USEPA, Drinking Water Research Division, Cincinnati, Ohio, 1979. Water depth approximately 8 cm.

TRANS-1,2-DICHLOROETHYLENE*

Structure



Other Names (31-33)

trans-acetylene dichloride; trans-dichloroethylene; trans-1,2-dichloroethene

This isomer of 1,2-dichloroethylene is a low-temperature solvent that is sometimes used to decaffeinate coffee or as a refrigerant.

Conventional Treatment

No data are available. See Discussion, Section 4.

Aeration

In a laboratory study where distilled water containing 217 μg/L trans-1,2-dichloroethylene was passed through a counter-current flow, diffused-air aerator, the Drinking Water Research Division found a 97 percent reduction in trans-1,2-dichloroethylene concentrations at a 15-to-1 air-to-water ratio. The aerator was a glass column 10cm (2.5 in) in diameter with a water depth of 1.2 m (4 ft). The contact time was 13 minutes. Other air-to-water ratios and corresponding percent removals are shown in Section 4, Figure 25.

Adsorption

Dobbs and Cohen (40) developed an adsorption isotherm for this solvent in distilled water using pulverized Filtrasorb® 300 granular activated carbon. From the Freundlich isotherm shown in Figure 8, the estimated adsorption capacity for this solvent at an equilibrium concentration of 100 μg/L is 0.9 mg/g. No field data are available on the adsorption of trans-1,2-dichloroethylene from contaminated waters.

Boiling

See Discussion, Section 4.

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*See Table 1, page 6, for properties.

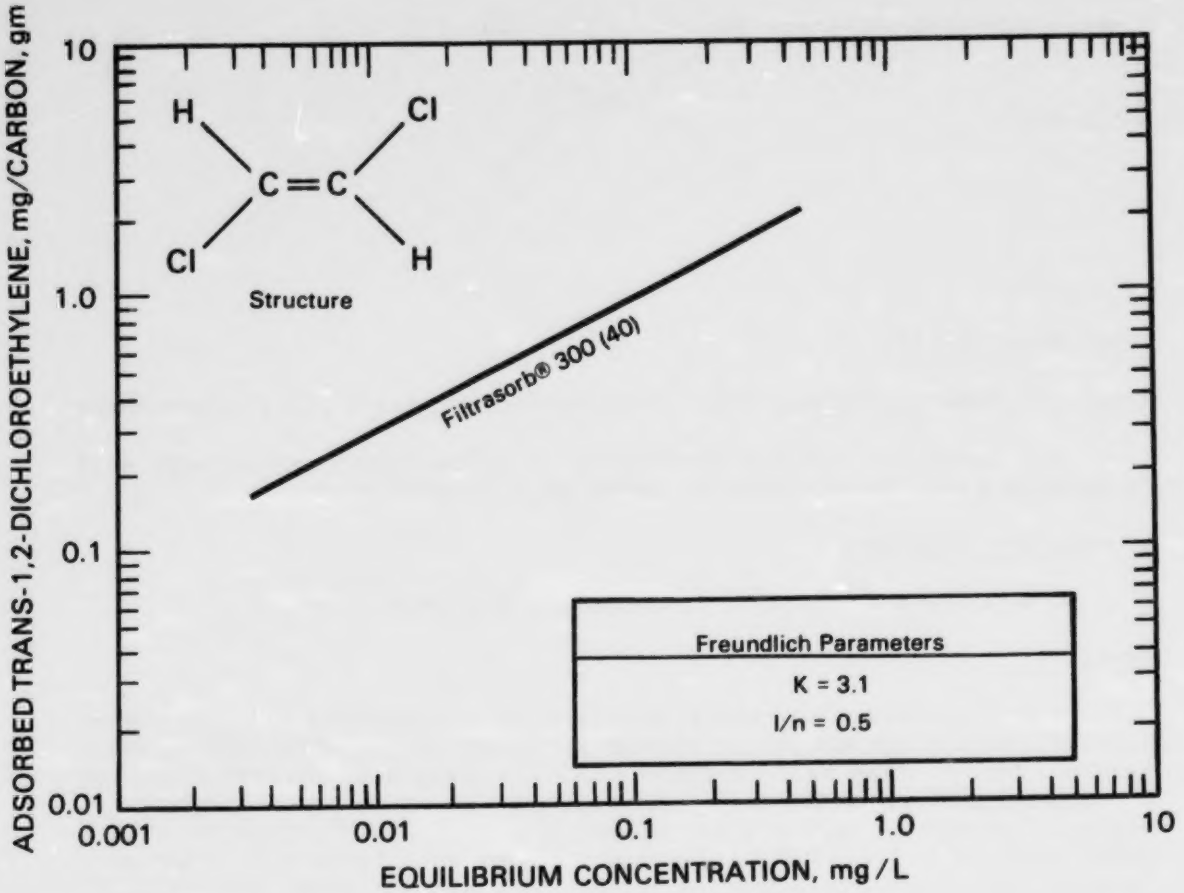
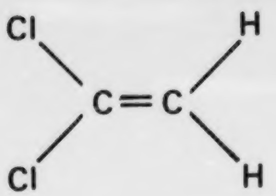


Figure 8. Isotherm for Trans-1,2-Dichloroethylene Adsorption on Activated Carbon.

1,1-DICHLOROETHYLENE*

Structure



Other Names (31-33)

1,1-DCE; 1,1-dichloroethene; vinylidene chloride; NC11-C54262

1,1-Dichloroethylene is commercially produced by dehydrochlorination of 1,1,2-trichloroethane (CH ClCHCl) by sodium hydroxide or lime. This solvent is used in the manufacturing of plastics and, more recently, in the production of 1,1,1-trichloroethane (17).

Conventional Treatment

No data are available. See Discussion, Section 4.

Aeration

This chlorinated solvent has a high Henry's Law Constant and should be easily removed by aeration.** This was the case in a New Jersey study in which 97 percent was removed at an air-to-water ratio of 4:1 and a 10-minute contact time. The influent concentration of 1,1-dichloroethylene was 122 µg/L, and the diffused-air device used is described in Table 2.

Adsorption

The Dobbs and Cohen (40) Freundlich isotherm for adsorption of 1,1-dichloroethylene in distilled water on pulverized Filtrasorb® 300 granular activated carbon is given in Figure 9. From the isotherm, the estimated adsorption capacity for this solvent at an equilibrium concentration of 100 µg/L is 1.2 mg/g.

A New Jersey study (see discussion of tetrachloroethylene for more information) examined adsorption of 1,1-dichloroethylene before and after aeration. Figure 10 illustrates the performance of Witcarb® 950 granular activated carbon and Ambersorb® XE-340 polymeric resin during a 60-week test period. When the adsorption system received non-aerated water, breakthrough (greater than 0.1 µg/L) was noted after passage of 22,400 m^3/m^3 (6.2 mg/g) for the activated carbon and 80,600 m^3/m^3 (20 mg/g) for the resin. Both adsorbents were still removing over 80 percent of the influent concentration of 1,1-dichloroethylene when the test was terminated. With the exception of the XE-340 resin for a brief period near the end of the study, both

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*See Table 1, page 6, for properties.

**See Discussion, Section 4, for relationship between Henry's Law Constant and aeration efficiency.

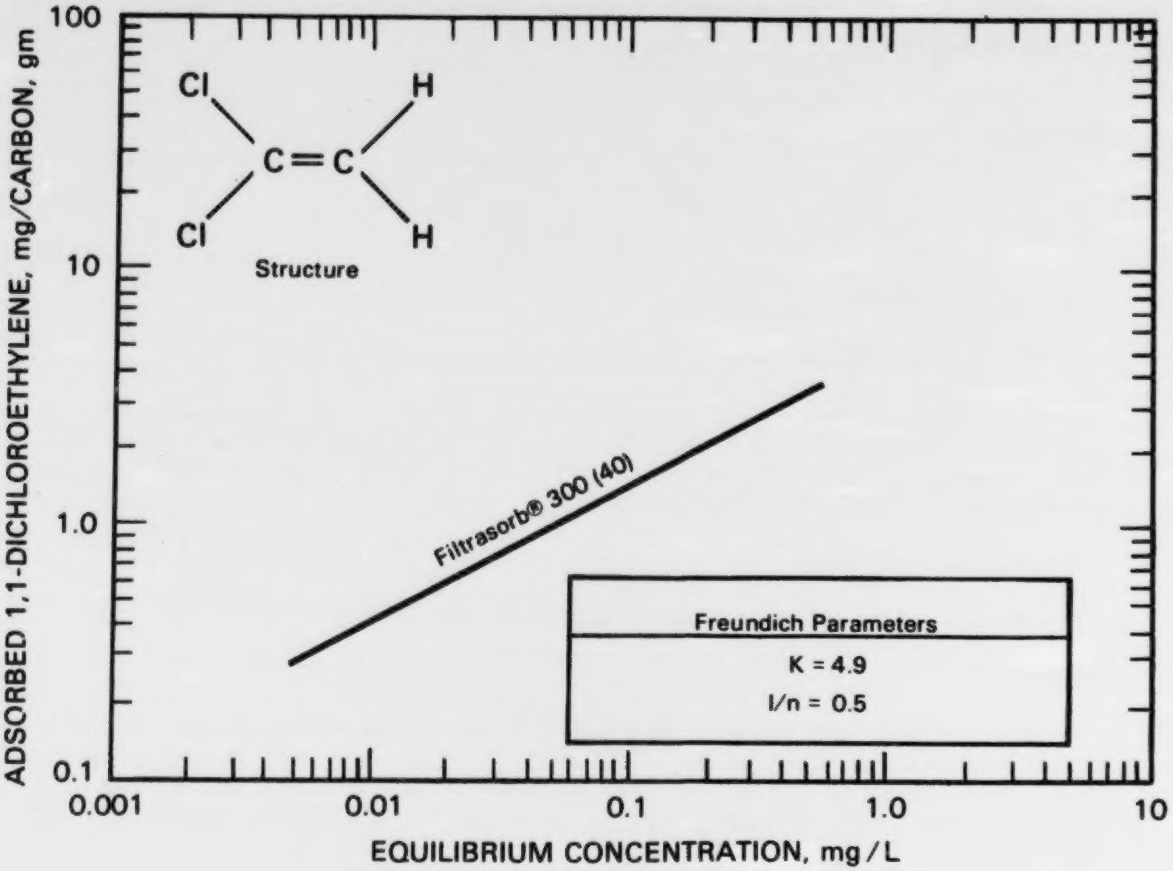


Figure 9. Isotherm for 1,1-Dichloroethylene Adsorption on Activated Carbon.

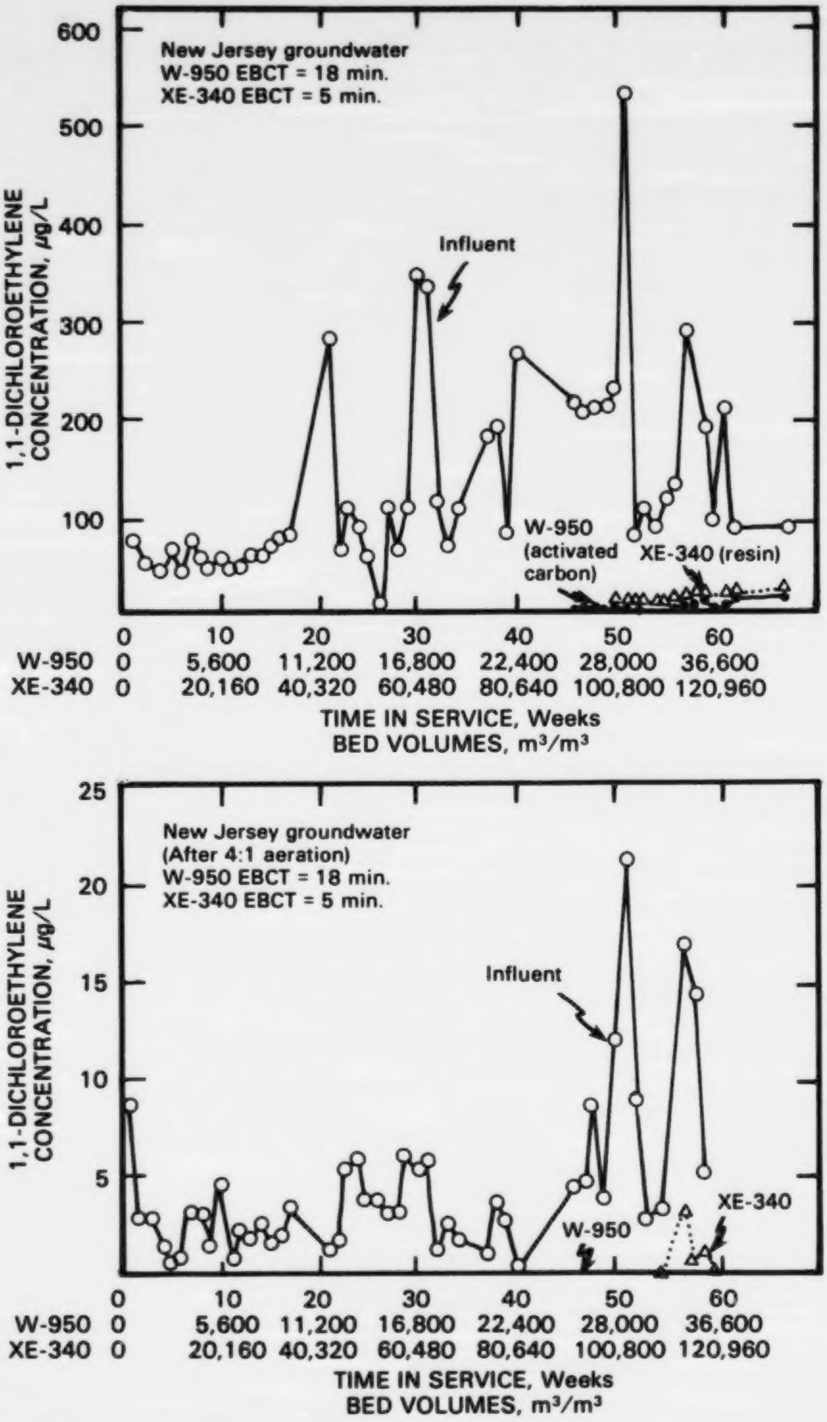


Figure 10. Removal of 1,1-Dichloroethylene on Granular Activated Carbon or Polymeric Resin.

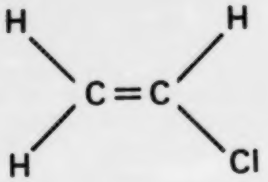
adsorbents removed the 1,1-dichloroethylene remaining after aeration to below detection.

Boiling

See Discussion, Section 4.

VINYL CHLORIDE*

Structure



Other Names (31-33)

chloroethylene; chloroethene; Chlorathene; Ethylene; Chloro-; ethylene monochloride; monochloroethene; monochloroethylene; VCM; Vinyl C monomer

Vinyl chloride is commonly produced by reacting chlorine gas with ethylene ($CH_2 = CH_2$) (49). Billions of kilograms of this solvent are used annually in the United States to produce polyvinyl chloride (PVC), the most widely used ingredient for manufacturing plastics throughout the world (50). Evidence is also mounting that vinyl chloride may be a biodegradation end-product of tri- and tetrachloroethylene under certain environmental conditions (16).

Special precautions are necessary to sample and analyze for vinyl chloride because of its low boiling point (high volatility). Unlike trichloroethylene, for example, vinyl chloride escapes detection in a routine analysis for trihalomethanes. For this reason, little definitive occurrence or treatment information exists on this contaminant in drinking water.

In 1978, Dressman and McFarren (5) conducted tests on PVC pipe. They sampled five water distribution systems that used PVC pipe and found vinyl chloride concentrations in the water ranging from 0.7 to 55 μg/L. They concluded that the vinyl chloride contamination levels were related to the vinyl chloride monomer residual in the pipe, and to whether or not the water flowed continuously or sat idle in the pipe. The authors pointed out, however, that producers of PVC pipe claim that changes later made in the manufacturing process lowered residual monomer in the pipe and thus reduced the vinyl chloride expected to leach into drinking water from new PVC pipe.

Conventional Treatment

Vinyl chloride was detected intermittently in a Southern Florida ground water. The average concentration reduction for this contaminant through the lime softening basins and filters was 25 to 52 percent (48). These losses were probably to the atmosphere around the open basins.

Aeration

No data are available. See Discussion, Section 4.

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*See Table 1, page 6, for properties.

Adsorption

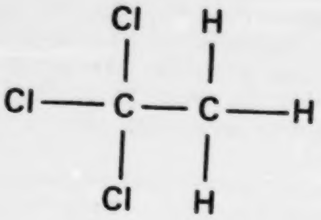
Finished water from a Southern Florida groundwater treatment plant was routed to four pilot scale granular activated carbon columns connected in series. Each column contained a 76-cm (30-in) depth of Filtrasorb® 400 activated carbon, and the empty bed contact time was approximately 6 minutes per column. Vinyl chloride concentrations in the influent ranged from below detection to 19 µg/L, and removal by adsorption on the activated carbon was erratic. For example, to maintain an effluent concentration of vinyl chloride below 0.5 µg/L, the estimated activated carbon loading was 810, 1250, 2760, and 2050 m^3/m^3 for empty bed contact times of 6, 12, 19, and 25 minutes, respectively (48, 51). Similarly, vinyl chloride was reported to be poorly removed on Ambersorb®XE-340 synthetic resin (51).

Boiling

No data are available.

1,1,1-TRICHLOROETHANE[*]

Structure



Other Names (31-33)

methylchloroform; Chloroethene; Aerothene TT; Chlorten; NC1-C04626; alpha-trichloroethane; -t; Chlorothane; Chlorothene NU; Chlorothene VG; Inhibisol; methyltrichloromethane; trichloroethane

1,1,1-Trichloroethane is commercially produced by reacting chlorine with vinyl chloride ($CH_2 = CHCl$) or by acidifying 1,1-dichloroethylene (also known as vinylidene chloride, $CH_2 = CCl_2$) with hydrochloric acid. 1,1,1-Trichloroethane has replaced trichloroethylene in many industrial and household products. It is the principal solvent in septic tank degreasers, cutting oils, inks, shoe polishes, and many other products (17, 34, 52).

Among the volatile organics found in ground waters, 1,1,1-trichloroethane and trichloroethylene are encountered most frequently and in the highest concentrations. USEPA Region III, has investigated an industrial well water situation in Pennsylvania, in which the wells most distant from the pollution source contained trace quantities of trichloroethylene and the wells nearest the pollution source(s) contained 1,1,1-trichloroethane. This possibly reflects the previous change in industrial solvent uses.[†] 1,1,1-Trichloroethane has also been identified in drinking water taken from surface sources. In one instance, a cleaning agent containing 1,1,1-trichloroethane was being used within the water treatment plant and the contaminants detected in the finished water could have come from that source (53).

Conventional Treatment

No data are available. See Discussion, Section 4.

Aeration

NKRE (37) observed a 66 to 85 percent reduction in (influent concentrations of 3 to 7 µg/L) 1,1,1-trichloroethane concentrations with the introduction of air at air-to-water ratios ranging from 5:1 to 30:1 (see discussion of trichloroethylene). The diffused-air aerator used in the USEPA's New Jersey study (see Figure 5) consistently achieved approximately 90 percent removal of 1,1,1-trichloroethane at a 4:1 air-to-water ratio. The influent concentration ranged from 170 to 280 μg/L. Similarly, McCarty's group (24) obtained high removals of 1,1,1-trichloroethane with both a packed bed degasifier and an ammonia stripping tower used for advanced wastewater treatment at Water Factory 21. The influent concentrations of 1,1,1-trichloroethane, however, were less than 5 μg/L.

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[*] See Table 1, page 6, for properties.

[†] Private communication, H.G. Beyer, USEPA Region III Water Supply Branch (1979).

Kelleher and fellow researchers (54) reported mixed results on an aeration study in Norwood, Massachusetts. They used a 10-cm (4-in) diameter glass column packed with glass raschig rings to a depth of 63 cm (25 in). Compressed air was blown up through the packing material as contaminated ground water trickled downward. With water from Well #4 (see Table 9) the removal of 1,1,1-trichloroethane ranged from 74 to 97 percent for a broad spectrum of aeration conditions, whereas from water of Well #3, the removal was poorer. This difference could not be explained.

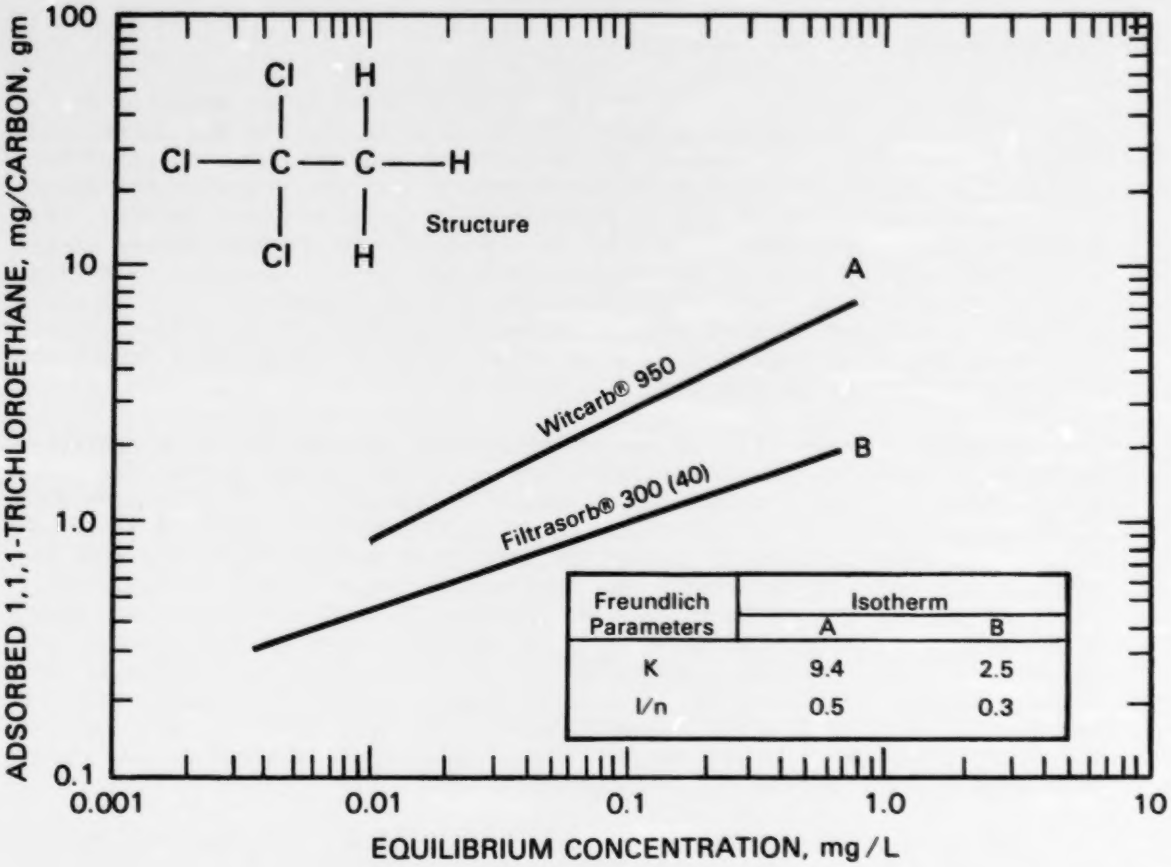
TABLE 9. REMOVAL OF 1,1,1-TRICHLOROETHANE FROM DRINKING WATER USING A PILOT SCALE FORCED DRAFT PACKED TOWER (54)

Effluent concentration of 1,1,1-trichloroethane, μg/L					
Source	Influent concentration, μg/L	Range of air-to-water ratios			
		1:1 to 10:1	11:1 to 20:1	21:1 to 50:1	>50:1
Well #4	110			13	5
	90	10	10		
	42	8	4	3	
Well #3	850		410	220	
	1200	460		350	49
	630	387	210		

Blanks indicate no tests conducted.

Adsorption

USEPA developed adsorption isotherms for 1,1,1-trichloroethane (Figure 11). Calculating on the basis of these isotherms, the average adsorption capacity for a 100 μg/L concentration of 1,1,1-trichloroethane is 1.6 mg/g. In a full-scale study at a water treatment plant in Florida, Ervin and Singley (55) found no difference in the removal efficiency of four powdered activated carbons: pulverized Calgon GW; Huskey Watercarb® Plus; ICI Hydrodarco® B; and Westvaco Aqua Nuchar® II. At a dosage of approximately 7 mg/L and a 2-hour contact time, powdered activated carbon removed at best 15 to 20 percent of an 18 μg/L 1,1,1-trichloroethane influent concentration in a



CCl_3CH_3

Freundlich Parameters	Isotherm A	Isotherm B
K	9.4	2.5
I/n	0.5	0.3

Figure 11. Isotherms for 1,1,1-Trichloroethane Adsorption on Activated Carbon.

Florida ground water (39, 52).

Figure 12 illustrates some of the USEPA Drinking Water Research Division pilot scale adsorption project results from studies in New Jersey and Connecticut. While the amount of contaminant and the type of adsorbent varied, the length of service to breakthrough for the granular activated carbon only ranged from 12,000 to 15,000 m^3/m^3. Expressed as a loading, the activated carbon adsorbed from 0.02 to 7.5 mg/g. In the New Jersey study (described in discussion of tetrachloroethylene), activated carbon receiving aerated water with an average 1,1,1-trichloroethane concentration of 23 µg/L produced an effluent with no detectable amounts during a 58-week-long study. This resulted in am empirical loading of at least 1.9 mg/g and a length of service greater than 32,000 m^3/m^3.

Kelleher's group (54) conducted adsorption experiments at a contaminated well site in Massachusetts. They used four 10-cm (4-in) diameter glass columns, each containing a 60-cm (2-ft)depth of Filtrasorb® 400 granular activated carbon in series for a total adsorbent depth of 2.5 m (8 ft). These were operated to assess the effects of contact time, and time to breakthrough was not reported. The loadings to reach 5 µg/L of 1,1,1-trichloroethane in the effluent from an applied 100 µg/L concentration, were 0.26 mg/g, 0.51 mg/g, and 0.74 mg/g for contact times of 7.5 minutes, 15 minutes, and 22.5 minutes, respectively. These results are included in the summary portion of Figure 12. The total organic carbon (TOC) concentration was over 2 mg/L in the Massachusetts water, yet less than 0.5 mg/L in the Connecticut and New Jersey water; thus, competitive adsorption may have accounted for differences in performance.

Neeley and Isacoff (42) and Isacoff and Bittner (56)compared Ambersorb®XE-340 resin to Filtrasorb® 400 granular activated carbon for removing 1,1,1-trichloroethane from a New Jersey well water. The experiment was conducted using 5-cm-long columns containing 15 cc of adsorbent and water shipped to their laboratory from the contaminated well. At a 270 liter per minute per cubic meter (2 gpm/ft^3) loading rate and 3.7-minute empty bed contact time, 1,1,1-trichloroethane at an average applied concentration of 450 µg/L broke through both adsorbents between 5000 and 6000 m^3/m^3. This produced a loading of approximately 4.2 mg/g.

A difference in adsorbent behavior was seen after contaminant breakthrough. The granular activated carbon column steadily became more exhausted, while the resin column continued to remove a large percentage of the solvent. Rather than having an incisive slope like the granular activated carbon, the slope of the breakthrough curve for the resin was gradual. Using water from the same contaminated source in New Jersey, the Drinking Water Research Division found with its pilot scale columns (Figure 5) that XE-340 removed to below detection 1,1,1-trichloroethane (average applied concentration of 237 µg/L) for almost 83,000 m^3/m^3 (33 mg/g). Why the service life found in the field study, Figure 12, was so much longer than the service life that was predicted from the laboratory studies (56) cannot be explained.

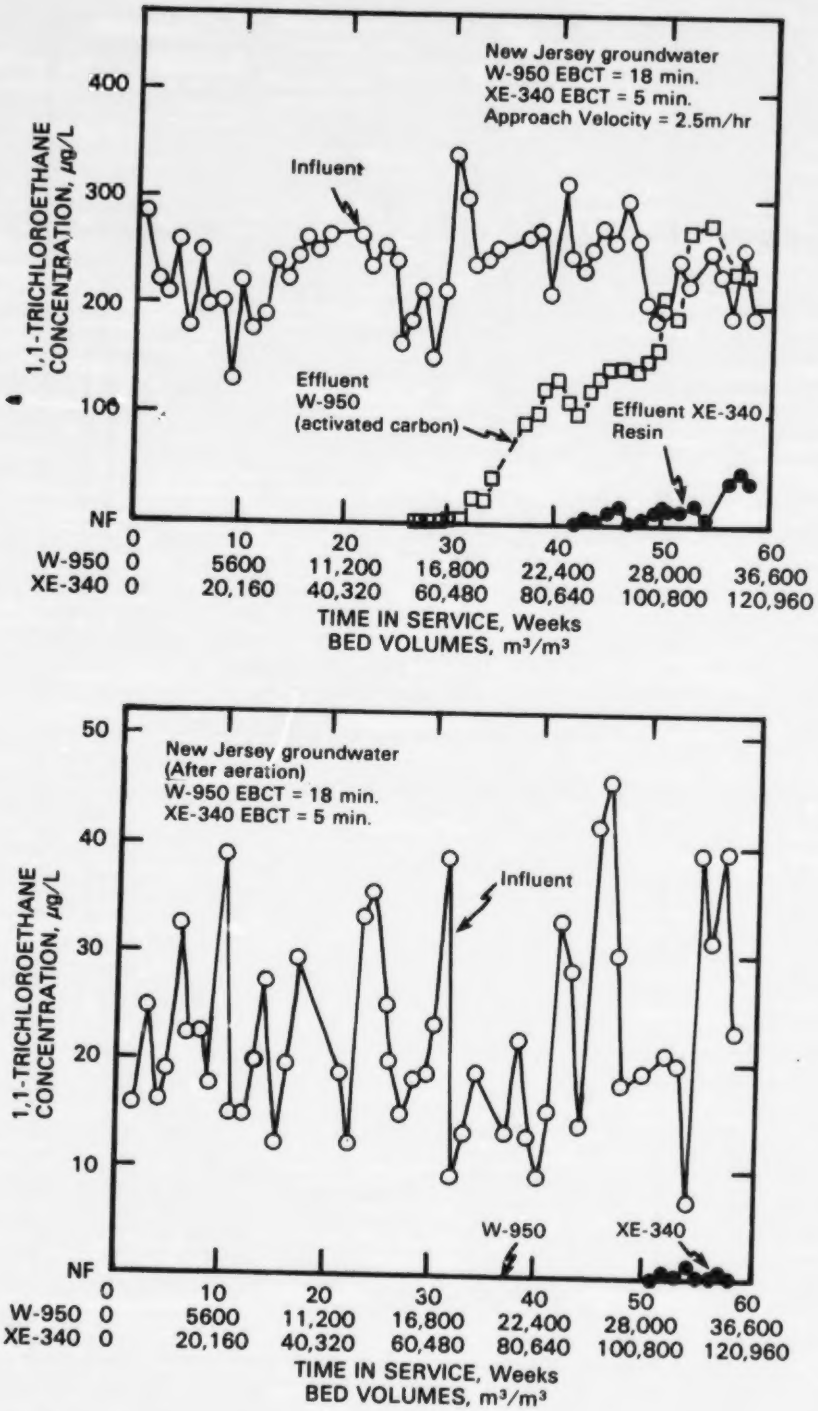


Figure 12. Removal of 1,1,1-Trichloroethane on Granular Activated Carbon or Polymeric Resin.

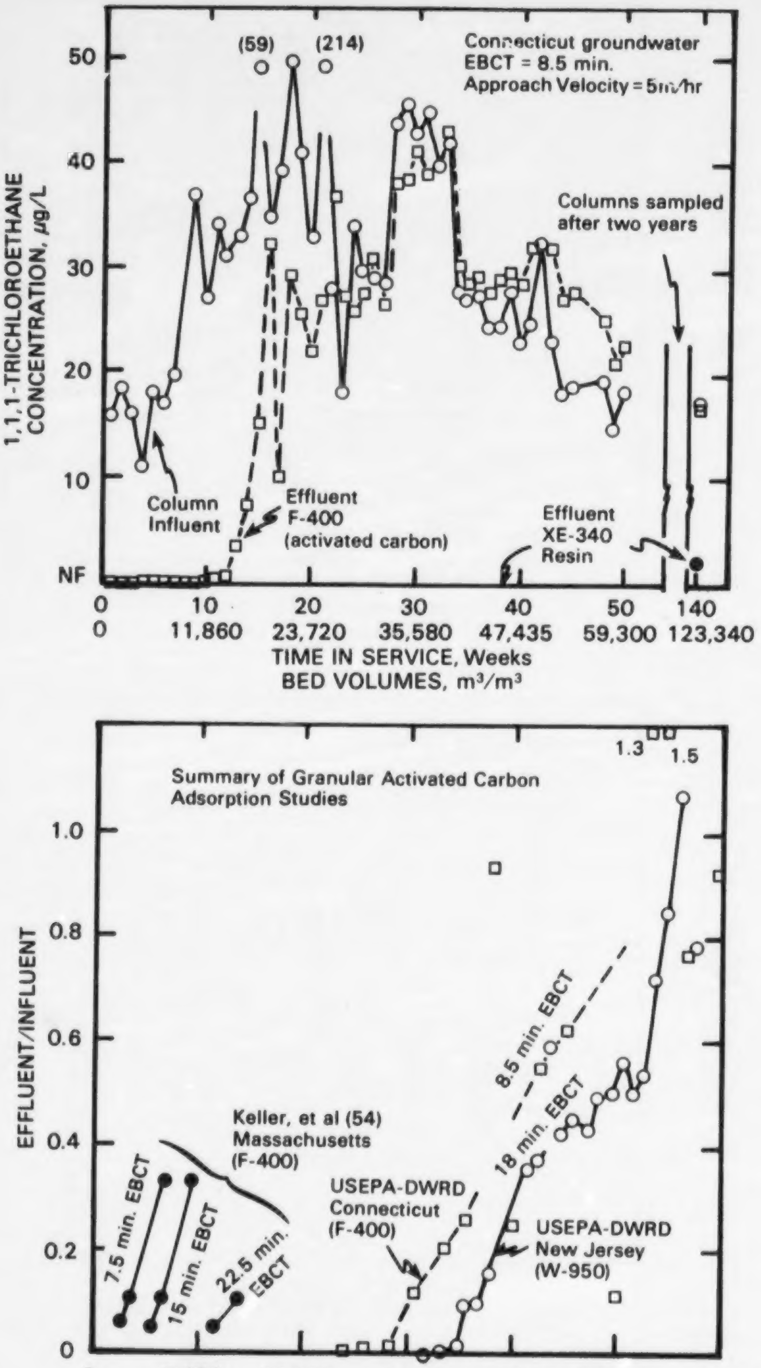


Figure 12. (Cont'd.)

In the New Jersey study, a column containing Ambersorb® XE-340 and receiving aerated water (see Figure 5) with an average 1,1,1-trichloroethane concentration of 23 µg/L, had detectable quantities of the solvent in the effluent after 52 weeks. This corresponded to a loading of 101,000 m^3/m^3 (3.9 mg/g).

In the Connecticut project, a column containing Ambersorb® XE-340 (3.5-minute empty bed contact time) was sampled weekly for one year and then next sampled a year later. Breakthrough was evident at the end of the first year and after 62,000 m^3/m^3, or 3.3 mg/g. The adsorbent was not exhausted even at the end of the second year.

Boiling

Lataille (44) found that, depending on depth, only 1 to 20 percent of an initial 1,1,1-trichloroethane concentration remained after 5 minutes of boiling. Similarly, personnel in the Rhode Island State Laboratories (57) found an average of only 2 percent of the starting 1,1,1-trichloroethane concentration remaining after 5 minutes of boiling contaminated drinking water samples (Table 10).

TABLE 10. REMOVAL OF 1,1,1-TRICHLOROETHANE FROM DRINKING WATER BY BOILING

Water sample	Time of boiling, minutes	Concentration, µg/L			
Lexington, MA* tap water "spiked" with 1,1,1-trichloroethane	0 (before heating)	680	1350	2700	1900
	5	8	23	35	5[a],27[b],360[c]
Contaminated drinking water in Rhode Island	0 (before heating)	37†			
	5	1			

*After Lataille (44)

[a] Water depth = 2 cm

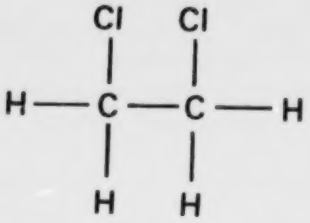
[b] Water depth = 5 cm

[c] Water depth = 11 cm

†Average of 12 tests with water having 1,1,1-trichloroethane concentrations ranging from 2 to 166 µg/L. After Reference 57.

1,2-DICHLOROETHANE*

Structure



$$\begin{array}{ccccc} & Cl & & Cl & \\ & | & & | & \\ H - & C & - & C & - H \\ & | & & | & \\ & H & & H & \end{array}$$

Other Names (31-33)

1,2-dichloroethane; Borer Sol; Brocide; Destraxol Borer-Sol; Dichloroemulsion; Di-Chloro-Mulsion; dichloroethane; Alpha, Beta-Dichloroethane; dichloroethylene; Dutch Liquid; EDC, ENT 1,656; ethane dichloride; ethylene chloride; ethylene dichloride; glycol dichloride; NC1-C00511; acetylene dichloride; Dioform

1,2-Dichloroethane is used as a solvent for fats, oils, waxes, gums, and resins (31).

Conventional Treatment

In a Louisiana study (35, 58) 1,2-dichloroethane with a mean concentration of 8 μg/L was not removed by coagulation and filtration.

Aeration

This contaminant is not easily removed from water by aeration. For example, Symons and fellow researchers (8) reported that air applied at an air-to-water ratio of 4:1 removed only 40 percent of the 1,2-dichloroethane from a contaminated well water in New Jersey.

Adsorption

The USEPA developed adsorption isotherms (Figure 13) for the removal of 1,2-dichloroethane in distilled water at a concentration of 100 μg/l by pulverized granular activated carbon. From these data, the estimated carbon's capacity at equilibrium ranged from 0.5 to 1.8 mg 1,2-dichloroethane/gram carbon. In a New Jersey study, Witcarb® 950 granular activated carbon maintained the effluent concentration of 1,2-dichloroethane below 0.1 μg/L for 31 weeks when the influent concentration averaged 1.4 μg/L. This yielded a loading of approximately 0.1 mg 1,2-dichloroethane/g carbon (17,400 m^3/m^3) to breakthrough. Ambersorb® XE-340 resin showed breakthrough after 54 weeks of service and a loading of approximately 0.3 mg 1,2-dichloroethane/g carbon (108,860 m^3/m^3).

In studies by DeMarco and others (35) and DeMarco and Brodtmann (58) in Louisiana, 1,2-dichloroethane at an average concentration of 8 μg/L was

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*See Table 1, page 6, for properties.

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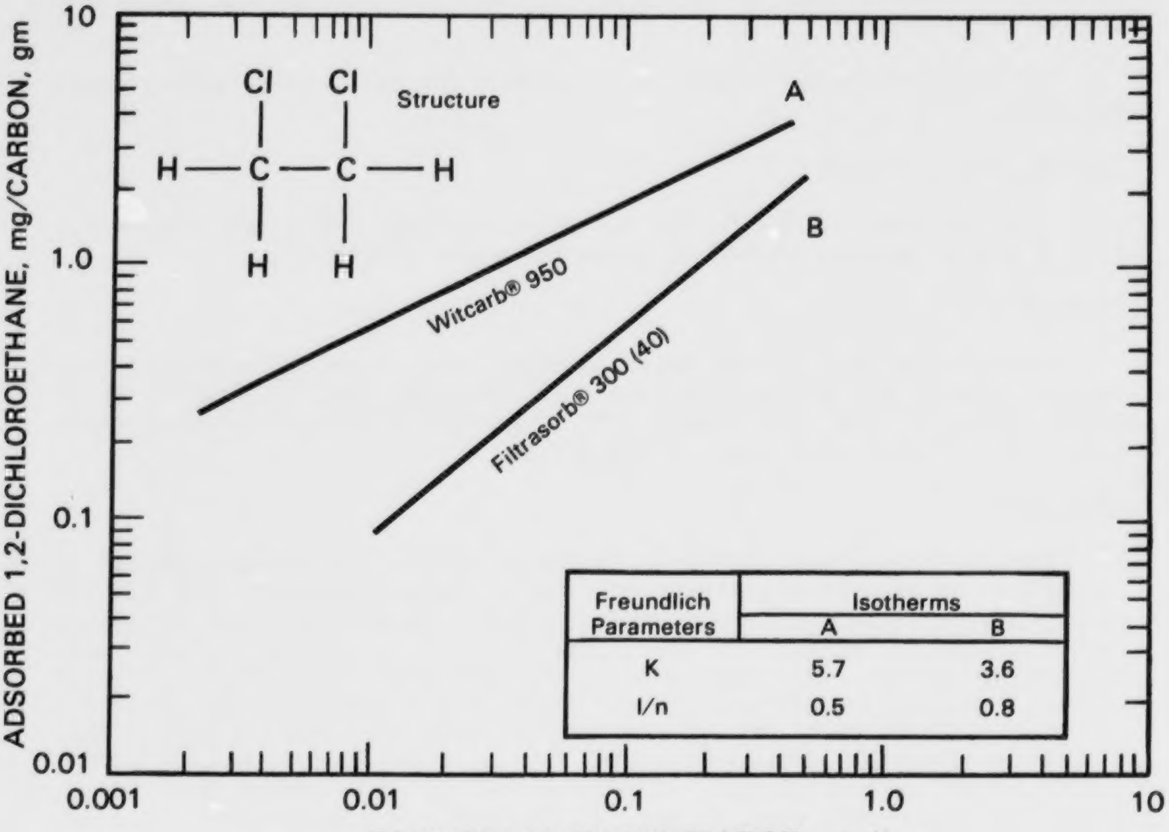
removed to a concentration of less than 0.1 μg/L for 39 days by a full-scale adsorber containing a 76-cm depth (30-in) of Nuchar® WV-G granular activated carbon (20-minute empty bed contact time). The equivalent loading was 1725 m^3 of water per m^3 of activated carbon or expressed in another way, 0.3 mg 1,2-dichloroethane per gram of activated carbon.

Boiling

See Discussion, Section 4.

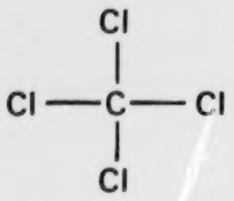


Freundlich Parameters	Isotherms A	Isotherms B
K	5.7	3.6
I/n	0.5	0.8

Figure 13. Isotherms for 1,2-Dichloroethane Adsorption on Activated Carbon.

CARBON TETRACHLORIDE*

Structure



Other Names (31-33)

tetrachloromethane; perchloromethane; Necatorina; Benzinoform; methane tetrachloride; methane, tetrachloro-; Necatorine; ENT 4,705; Halon 104; carbon chloride; Carbona; Flukoids; R10; Tetrafinol; Tetraform; Tetrasol; Univerm; Vermoestricid

Carbon tetrachloride was once a popular household solvent, a frequently used dry cleaning agent, and a charging agent for fire extinguishers. Since 1970, however, carbon tetrachloride has been banned from all use in consumer goods in the United States, and in 1978, it was banned as an aerosol propellant (59). Currently, its principal use is in the manufacture of flurocarbons, which are used as refrigerants and, to a lesser degree, in the making of grain fumigants. This solvent is a known contaminant in chlorine produced by the graphite-anode method (2), and chlorinated drinking water can become contaminated with carbon tetrachloride from this source (3, 60, 61). The American Water Works Association (AWWA) is rewriting chlorine specifications, and this will perhaps minimize carbon tetrachloride contamination resulting from chlorination.

Conventional Treatment

Incidental to a study on trihalomethanes, the USEPA detected carbon tetrachloride in the Ohio River and in the City of Cincinnati drinking water in 1976 and 1977 (Figure 14). Between July 1976, and February 1977, the concentration of this contaminant in the untreated water was 16.3 µg/L and in the treated water 16.0 µg/L, indicating that no net removal resulted from powdered activated carbon addition (2 to 4 mg/L), coagulation, settling, and filtration.

Aeration

Laboratory studies by the Drinking Water Research Division showed that aeration with the diffused-air aerator (discussed in the section on trichloroethylene treatment and also in Table 1) at a 4:1 air-to-water ratio could remove 91 percent of the carbon tetrachloride (8).

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*See Table 1, page 6, for properties.

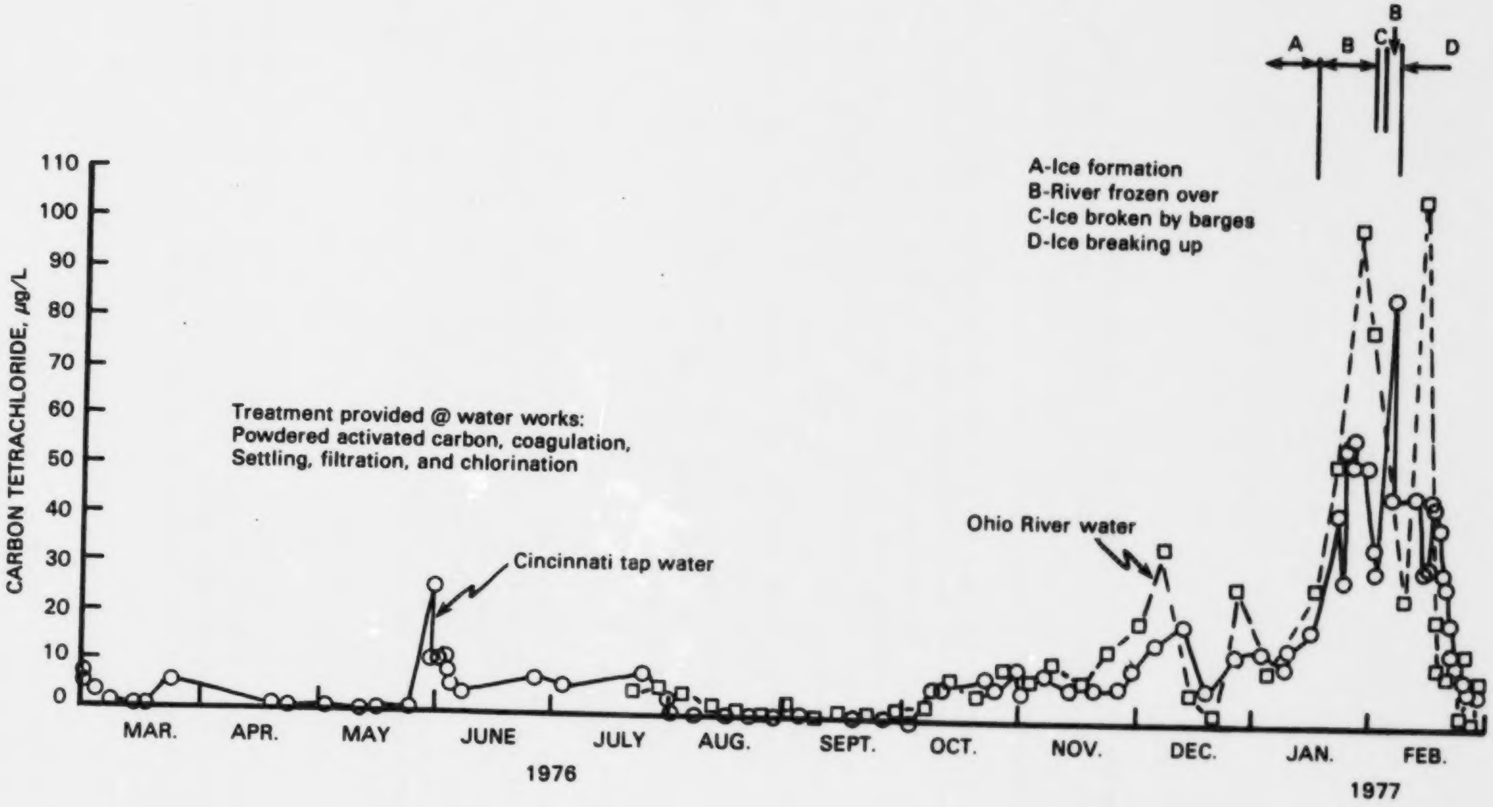


Figure 14. Carbon Tetrachloride in Raw and Treated Water at Cincinnati, Ohio.

Adsorption

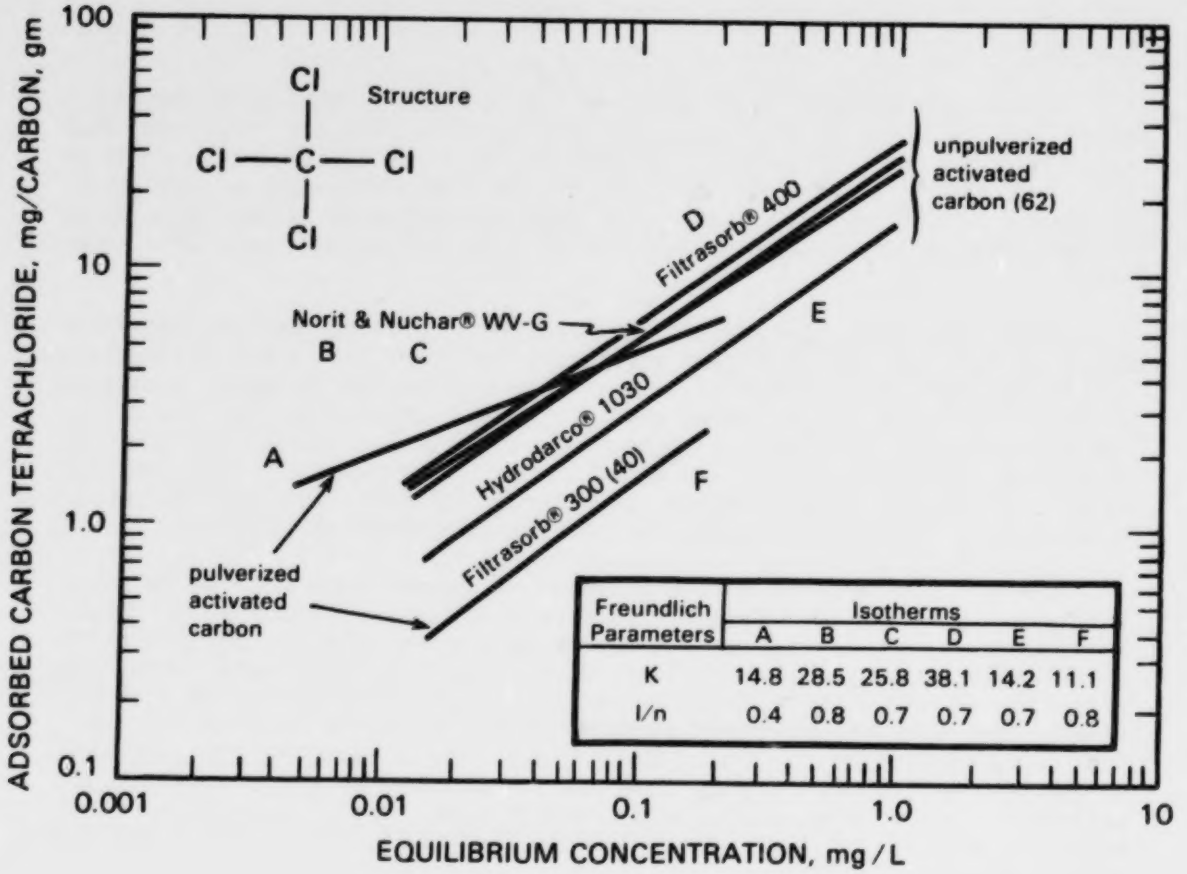
Lykins and DeMarco (61) reviewed the treatment data generated by a water utility using Ohio River water during 1976-1977 and concluded that consistent removals of carbon tetrachloride were not obtained with powdered activated carbon treatment. Differences could be attributed to analytical variation. USEPA studies showed that powdered activated carbon doses up to 30 mg/L removed only about 10 percent of this contaminant from Ohio River water.

Dobbs and Cohen (40), Weber and Pirbazari (62), and the Drinking Water Research Division have developed adsorption isotherms for carbon tetrachloride using different protocols and different types of granular activated carbon (Figure 15). From these studies, it was determined that the calculated adsorption capacity for carbon tetrachloride, at an equilibrium concentration of 100 µg/L, on activated carbon is between 1.6 mg/g and 7.0 mg/g. It is not known whether this range reflects true differences in adsorbents or simply differences in isotherm determination technique.

Symons (63) reported on the behavior of carbon tetrachloride in water that was applied to pilot scale adsorbers containing Filtrasorb® 400 granular activated carbon. Two adsorbers, one with a 5-minute and the other with a 10-minute empty bed contact time, were exposed to Cincinnati, Ohio, tap water for 18 weeks when carbon tetrachloride was detected in the influent water. The mean concentration of the contaminant in the water was 12 µg/L, and this was removed to less than 0.1 µg/L for 3 weeks by the activated carbon with a 5-minute contact time and for between 14 and 16 weeks by the activated carbon with a 10-minute contact time. This corresponds to an empirical loading range of approximately 6000 and 14,000 m^3/m^3 (0.2 and 0.4 mg/g), respectively.

In the fall of 1976, three granular activated carbons manufactured in France were also exposed to tap water in the USEPA Drinking Water Research Division laboratory in Cincinnati. Two of the materials, PICA-A and PICA-B, behaved similarly to the Filtrasorb® 400, but the third, PICA-C, had no capacity for carbon tetrachloride. Further, PICA-C had no capacity for total organic carbon or for trihalomethanes (63), leading the investigators to suspect that the material was either poorly activated or not activated at all.

Symons and fellow researchers (8) reported that Ambersorb® XE-340 removed carbon tetrachloride from Cincinnati, Ohio, drinking water for about the same length of time as the granular activated carbon did. Although the length of service to breakthrough was similar to that for granular activated carbon, the shape of the adsorption and desorption curves were quite different. For activated carbon, desorption was evident when influent concentrations of the contaminant declined. The resin, on the other hand, showed some desorption, but much less than the granular activated carbon did (Figure 16).



Freundlich Parameters	Isotherms A	B	C	D	E	F
K	14.8	28.5	25.8	38.1	14.2	11.1
l/n	0.4	0.8	0.7	0.7	0.7	0.8

Figure 15. Isotherms for Carbon Tetrachloride Adsorption on Activated Carbon.

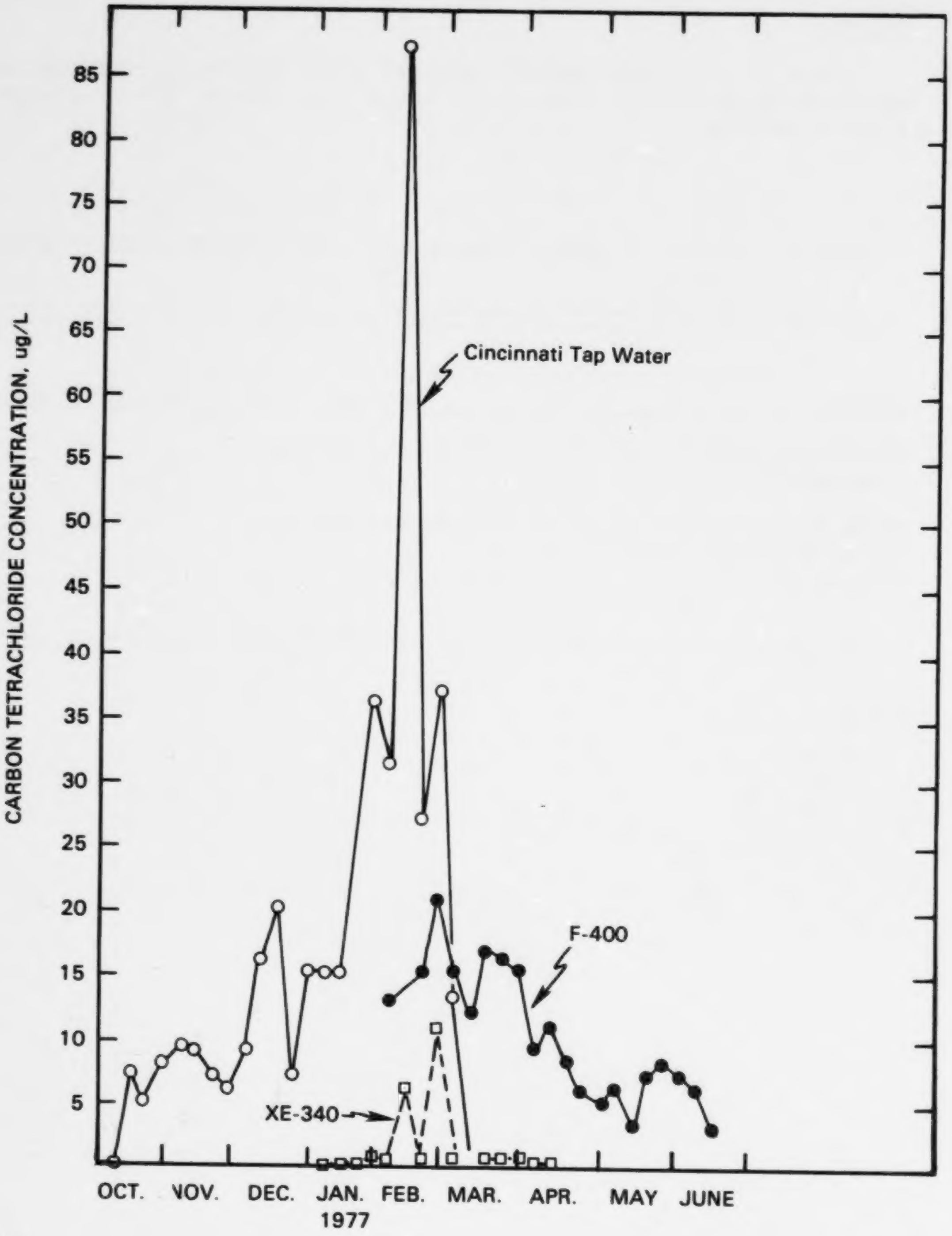


Figure 16. Desorption of Carbon Tetrachloride from Granular Activated Carbon and Polymeric Resin.

Boiling

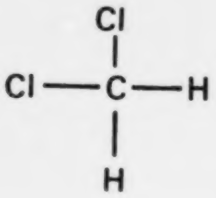
Table 11 lists some results obtained after boiling water contaminated by carbon tetrachloride. About 1 percent or less remains after 5 minutes of vigorous boiling.

TABLE 11. REMOVAL OF CARBON TETRACHLORIDE FROM DRINKING WATER BY BOILING

Sample	Time of boiling, minutes	Concentration, μg/L
Cincinnati, Ohio (tap water)	0 (before heating)	30
	5	<0.1
Rhode Island State Health Department (57) (tap water)	0 (before heating)	188
	5	2

METHYLENE CHLORIDE*

Structure



Other Names (31-33)

dichloromethane; Aerothene MM; methylene dichloride; Narkotil; R30; Solaesthin; Solmethine; methane dichloride; methylene bichloride; NC1-C50102

Methylene chloride is commercially produced by reacting methane directly with chlorine at approximately 500°C, or by reacting chlorine with methyl chlorine (CH_3Cl). The latter process is more predominant (17). Methylene chloride is a common ingredient in paint and varnish strippers, is an extraction solvent for decaffeinating coffee, an extraction solvent in analytical laboratories, and a carrier solvent in the textile industry. It is used extensively to make flexible foams in the urethane industry, and is also used to make pharmaceutical products such as steroids, antibiotics, and vitamins. Its uses in aerosols and as a vapor degreasing solvent are rapidly increasing. In 1977, the Nassau County, New York, Department of Public Works estimated that thousands of gallons of methylene chloride were being used annually as a cesspool cleaner and drain opener (52). Methylene chloride has been detected sporadically by the Drinking Water Research Division during analyses of water samples from pilot scale studies for other volatile compounds.

Conventional Treatment

No data are available. See Discussion, Section 4.

Aeration

In a laboratory study where distilled water containing an average of 225 μg/L methylene chloride was passed through a diffused-air aerator, the Drinking Water Research Division found an 82 percent reduction in methylene chloride concentrations at a 15:1 air-to-water ratio. Other aeration conditions and corresponding percent removals are shown in Section 4, Figure 25.

Adsorption

Dobbs and Cohen (40) developed an adsorption isotherm for methylene chloride in distilled water using pulverized Filtrasorb® 300 activated carbon. Weber's group (17) used distilled water and Filtrasorb® 400. These data are illustrated in Figure 17 as Freundlich isotherms. When methylene chloride has an equilibrium concentration of 100 μg/L, the capacity predicted from these isotherms is approximately 0.2 mg/g.

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*See Table 1, page 6, for properties.

O'Brien and fellow researchers (64) reported a carbon usage of 3.9 lb/1000 gal to maintain an effluent concentration of less than 1 μg/L in a situation in which methylene chloride in a ground water was typically above 20 mg/L. They used two activated carbon beds in series with an empty bed contact time of 262 minutes.

Boiling

See Discussion, Section 4.

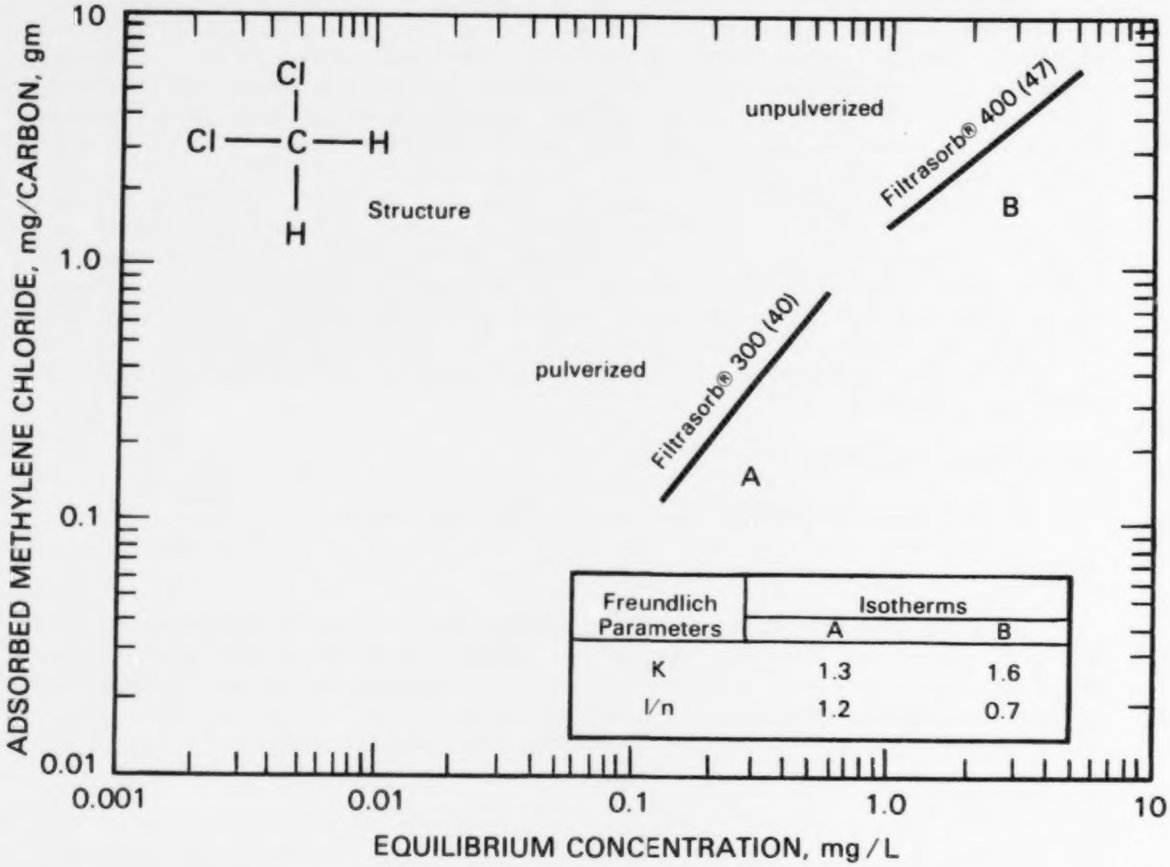
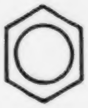


Figure 17. Isotherms for Methylene Chloride Adsorption on Activated Carbon.

BENZENE*

Structure



Other Names (31-33)

Benzole; Benzol; coal naphtha; carbon oil; cyclohexatriene; phene; phenyl; hydride; pyrobenzol; pyrobenzole; mineral naphtha; motor benzol; nitration benzene; (6) annulene; bicarburet of hydrogen

Destructive distillation of one ton of bituminous coal produces approximately 3 to 4 gallons of light oil, fractional distillation of this light oil is one commercial means of producing benzene. However, some amount of benzene is present in nearly all crude oils, and production of benzene from petroleum and petrochemical sources far exceeds that from coal. Other means of producing benzene include synthesis from acetylene and hydrocarbons, such as hexane. Benzene is used primarily in the synthesis of styrene (for plastics), phenol (for resins), and cyclohexane (for nylon). Other uses include the production of detergents (alkylbenzenes), drugs, dyes, and insecticides. Benzene is still being used as a solvent and as a component of gasoline (17).

Conventional Treatment

No data are available. See Discussion, Section 4.

Oxidation

Hoigne and Bader removed 97 percent of 80 μg/L benzene in lake water with 2.8 mg/L ozone (46).

Aeration

No data are available. See Discussion, Section 4.

Adsorption

Dobbs and Cohen (40) developed an adsorption isotherm for benzene in distilled water using pulverized Fitrasorb® 300 granular activated carbon. Benzene was measured by ultraviolet absorbence, and this necessitated using relatively high (20 mg/L) initial concentrations of benzene. Weber (62), on the other hand, developed isotherms on several different types of activated carbon by using gas chromatography and much lower initial benzene concentrations; this yielded considerably higher capacities. Figure 18 compares Weber's isotherm on Filtrasorb® 400 with that of Dobbs and Cohen. Weber's other Freundlich parameters for benzene are given in a figure presented later in the text (Figure 30). At an equilibrium concentration of 100 µg/L, the capacity for benzene predicted from Weber's isotherms ranged from 5.6 to 12.4 mg/g; the capacity from Dobbs' and Cohen's isotherm was 0.03 mg/g. When these procedures are compared for 1,4-dichlorobenzene, however, the resulting isotherms are in agreement.

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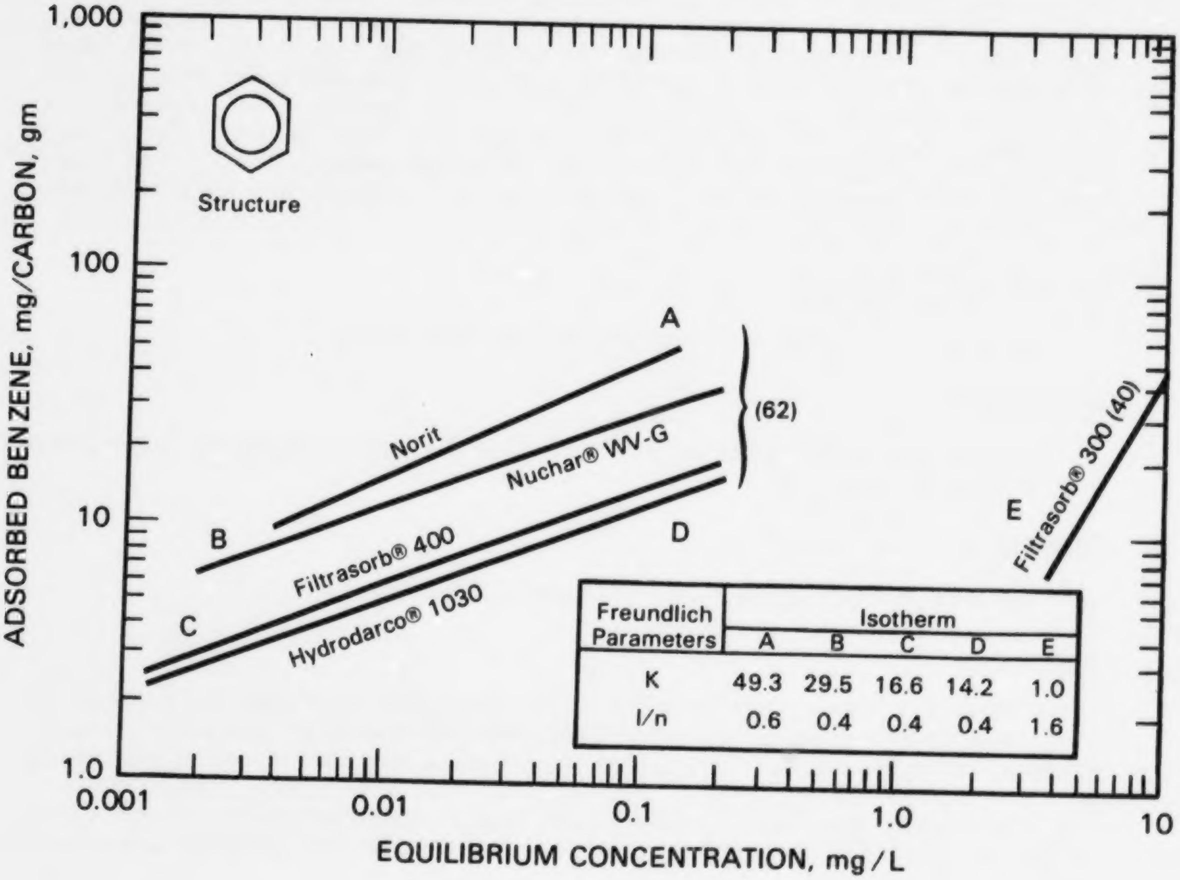
*See Table 1, page 6, for properties.

O'Brien's group (64) reported a carbon usage of 1.1 lb/1000 gal to reduce a typical benzene concentration of 5 mg/L to less than 10 µg/L in a contaminated ground water.

Boiling

See Discussion, Section 4.

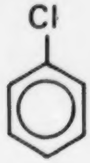


Freundlich Parameters	Isotherm				
	A	B	C	D	E
K	49.3	29.5	16.6	14.2	1.0
l/n	0.6	0.4	0.4	0.4	1.6

Figure 18. Isotherms for Benzene Adsorption on Activated Carbon.

CHLOROBENZENE*

Structure



Other Names (31-33)

benzene chloride; Chlorbenzene; Chlorbenzol; MCB; monochlorobenzene; phenylchloride; Monochlorobenzene

Chlorobenzene is produced by reacting chlorine with benzene in the presence of a catalyst such as ferric chloride ($FeCl_3$). Large amounts of chlorobenzene were produced during World War I to make picric acid, but currently its major use is as a solvent, in the manufacturing of phenol, DDT, insecticide, dyestuffs, and as an intermediate in the manufacturing of other compounds (17).

Conventional Treatment

When a chlorobenzene spill was tracked through a Louisville treatment plant over a 4-day period, raw water concentrations ranged from 0.1 to 5.0 µg/L, and finished water concentrations ranged from 1.1 to 8.5 mg/L, suggesting that conventional treatment (presedimentation, coagulation, sedimentation, filtration) provided poor control (65).

Aeration

In a laboratory study where distilled water containing an average of 97 µg/L chlorobenzene was passed through a diffused-air aerator, the Drinking Water Research Division found a 90 percent reduction in chlorobenzene concentrations at a 15:1 air-to-water ratio. Other aeration conditions and corresponding percent removals are shown in Section 4, Figure 26.

Adsorption

Dobbs' and Cohen's (40) adsorption isotherm for chlorobenzene in distilled water and pulverized Filtrasorb® 300 granular activated carbon is shown in Figure 19. Using this isotherm, at an equilibrium concentration of 100 µg/L, the predicted capacity is 9.3 mg chlorobenzene per gram of activated carbon. These isotherm data, however, were determined by ultraviolet absorbence and the initial chlorobenzene concentration was 26 mg/L. No field data are available for adsorption of chlorobenzene from contaminated waters.

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*See Table 1, page 6, for properties.

Boiling

See Discussion, Section 4.

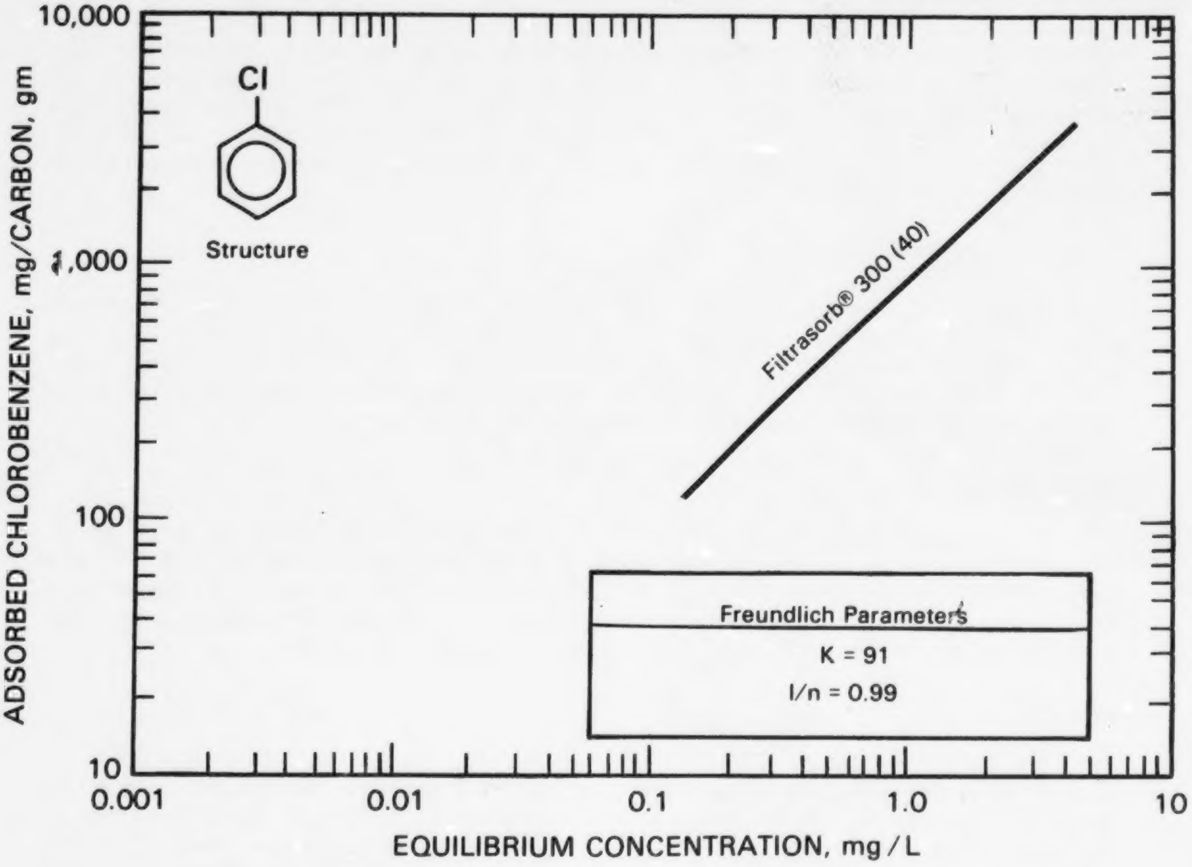
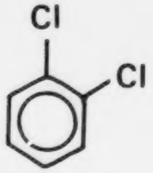


Figure 19. Isotherm for Chlorobenzene Adsorption on Activated Carbon.

1,2-DICHLOROBENZENE*

Structure



Other Names (31-33)

o-dichlorobenzene; ortho-dichlorobenzene; Chloroben; Dilatin DB; Dowtherm E; DCB; dichlorobenzene; o-Dichlorbenzol; Dizene; NCl-C54944; ODB; ODCB; two dichlorobenzene; Orthodichlorobenzol; Special Termite Fluid; Termitkill

1,2-Dichlorobenzene can be produced by chlorinating chlorobenzene in the presence of ferric chloride. It is used as a solvent for waxes, oils, and asphalts, as a metal degreasing agent, and as an insecticide for termites and locust borers (17, 33).

Conventional Treatment

No data are available. See Discussion, Section 4.

Aeration

In a laboratory study where distilled water containing an average of 151 μg/L 1,2-dichlorobenzene was passed through a diffused-air aerator, the Drinking Water Research Division found a 74 percent reduction in the average concentrations at a 15:1 air-to-water ratio. Other aeration conditions and corresponding percent removals are shown in Section 4, Figure 26.

Adsorption

Isotherm data are presented in Figure 20. For discussion, see 1,4-dichlorobenzene section.

Boiling

See Discussion, Section 4.

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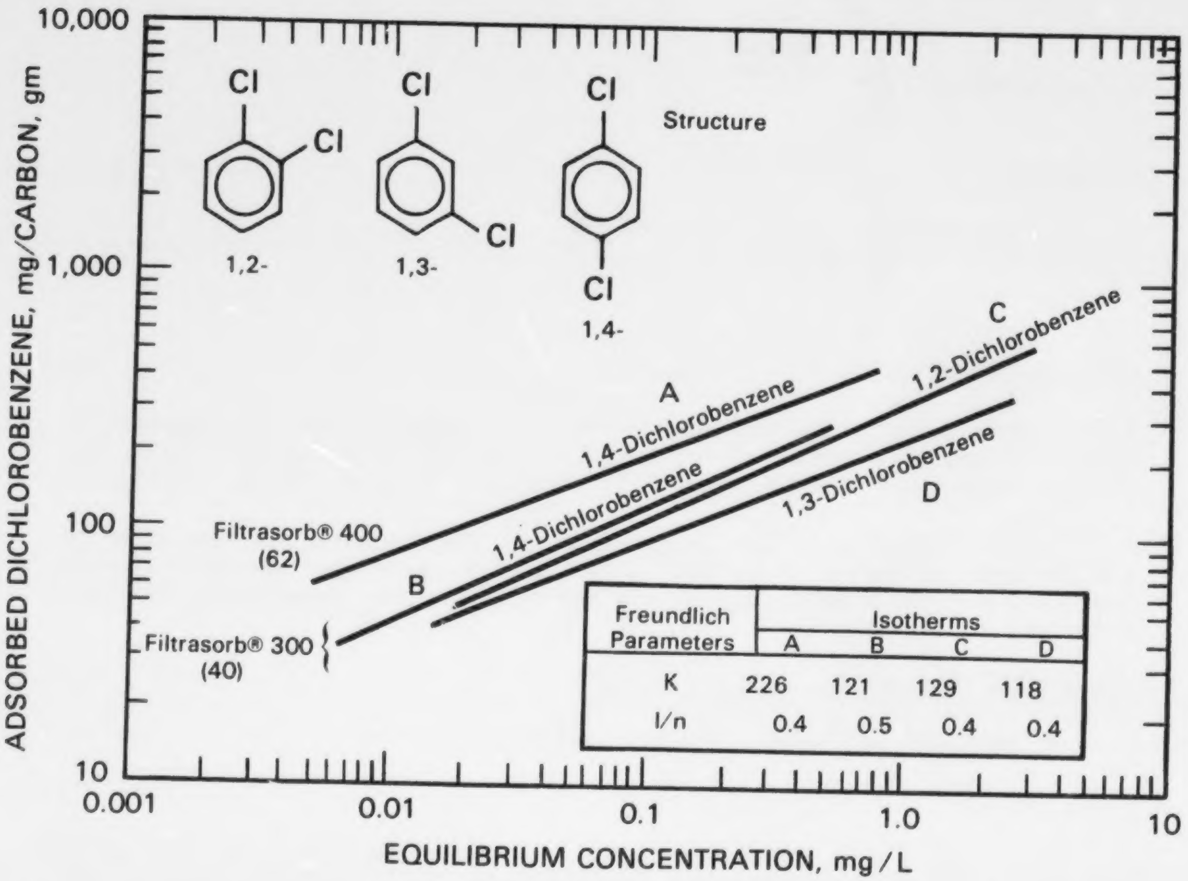
*See Table 1, page 6, for properties.

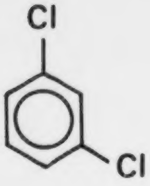


Freundlich Parameters	Isotherms			
	A	B	C	D
K	226	121	129	118
l/n	0.4	0.5	0.4	0.4

Figure 20. Isotherms for Dichlorobenzene Adsorption on Activated Carbon.

1,3-DICHLOROBENZENE*

Structure



Other Names (31, 33)

m-dichlorobenzene; m-Dichlorobenzol; meta-diclorobenzene; m-Phenylene dichloride; MCDB

1,3-Dichlorobenzene is usually produced by heating 1,2-dichlorobenzene or 1,4-dichlorobenzene under pressure in the presence of aluminum or hydrogen chloride (17). As a solvent, its behavior is similar to that of 1,2-dichlorobenzene.

Conventional Treatment

No data are available. See Discussion, Section 4.

Aeration

In a laboratory study where distilled water containing an average of 229 µg/L 1,3-dichlorobenzene was passed through a diffused-air aerator, the Drinking Water Research Division found a 79 percent reduction in 1,3-dichlorobenzene concentrations at a 15:1 air-to-water ratio. Other aeration conditions and corresponding percent removals are shown in Section 4, Figure 26.

Adsorption

Isotherm data are presented in Figure 20. For discussion, see 1,4-dichlorobenzene section.

Boiling

See Discussion, Section 4.

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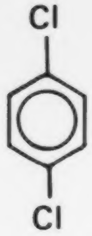
*See Table 1, page 6, for properties.

1,4-DICHLOROBENZENE*

Structure



Other Names (31-33)

p-dichlorobenzene; para-dichlorobenzene; Parazene; Di-chloricide; Paramoth; p-chlorophenyl chloride; Evola; Paradi; Paradow; PDB; Persia-Perazol; Santochlor

1,4-Dichlorobenzene is produced by chlorinating benzene in the presence of ferric chloride. Unlike 1,2-dichlorobenzene or 1,3-dichlorobenzene, 1,4-dichlorobenzene has a pungent, camphoric odor. Its principal uses are in moth control (balls, powders, etc.) and as lavoratory deodorants (17).

Conventional Treatment

No data are available. See Discussion, Section 4.

Aeration

In a laboratory study where distilled water containing an average of 225 μg/L, 1,4-dichlorobenzene was passed through a diffused-air aerator, the Drinking Water Research Division found a 77 percent reduction in 1,4-dichlorobenzene concentrations at a 15:1 air-to-water ratio. Other aeration conditions and corresponding percent removals are shown in Section 4, Figure 26.

Adsorption

Dobbs and Cohen (40) developed adsorption isotherms for the isomers of dichlorobenzene; Weber (62) included 1,4-dichlorobenzene in an adsorption study. All the results are shown in Figure 20. At an equilibrium concentration of 100 μg/L, 1,2-, 1,3-, and 1,4-dichlorobenzene would have an estimated capacity of 51, 47, and 58 mg solvent per gram of activated carbon, respectively. Initial isotherm concentrations ranged from 17 to 28 mg/L for all four isotherms. Dobbs and Cohen used ultraviolet absorbence, and Weber used gas chromatography to determine final concentrations. Little difference is noticeable among the various isomers with regard to their behavior on activated carbon. No field data are available for adsorption of 1,4-dichlorobenzene or its isomers from contaminated waters.

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*See Table 1, page 6, for properties.

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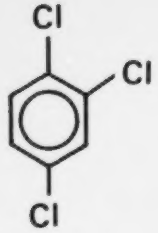
Boiling

See Discussion, Section 4.

1,2,4-TRICHLOROBENZENE*

Structure



Other Names (31-33)

Pyranol 1478; trichlorobenzene; unsym-trichlorobenzene

Chlorination of benzene yields three isomers of trichlorobenzene: 1,2,3-trichlorobenzene, 1,2,4-trichlorobenzene, and 1,3,5-trichlorobenzene. Of these isomers, only 1,2,4-trichlorobenzene is commercially produced in any quantity. It is mainly used as a dye carrier, and an herbicide intermediate, but it is also useful as a heat transfer medium, a dielectric fluid in transformers, and a degreaser (66).

Conventional Treatment

No data are available. See Discussion, Section 4.

Aeration

In a laboratory study where distilled water containing an average of 259 µg/L 1,2,4-trichlorobenzene was passed through a diffused-air aerator, the Drinking Water Research Division found a 68 percent reduction in concentration of this compound at a 15:1 air-to-water ratio. Other aeration conditions and corresponding percent removals are shown in Section 4, Figure 26.

Adsorption

Dobbs and Cohen (40) developed an adsorption isotherm for 1,2,4-trichlorobenzene in distilled water and pulverized Filtrasorb® 300 granular activated carbon. They used ultraviolet absorbence and an initial concentration of 15 mg/L. Using the Freundlich parameters given in Figure 21 at an equilibrium concentration of 100 µg/L, the capacity for this organic compound on activated carbon is 77 mg 1,2,4-trichlorobenzene per gram activated carbon. No field data are available for adsorption of trichlorobenzene from contaminated water.

Boiling

See Discussion, Section 4.

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*See Table 1, page 6, for properties.

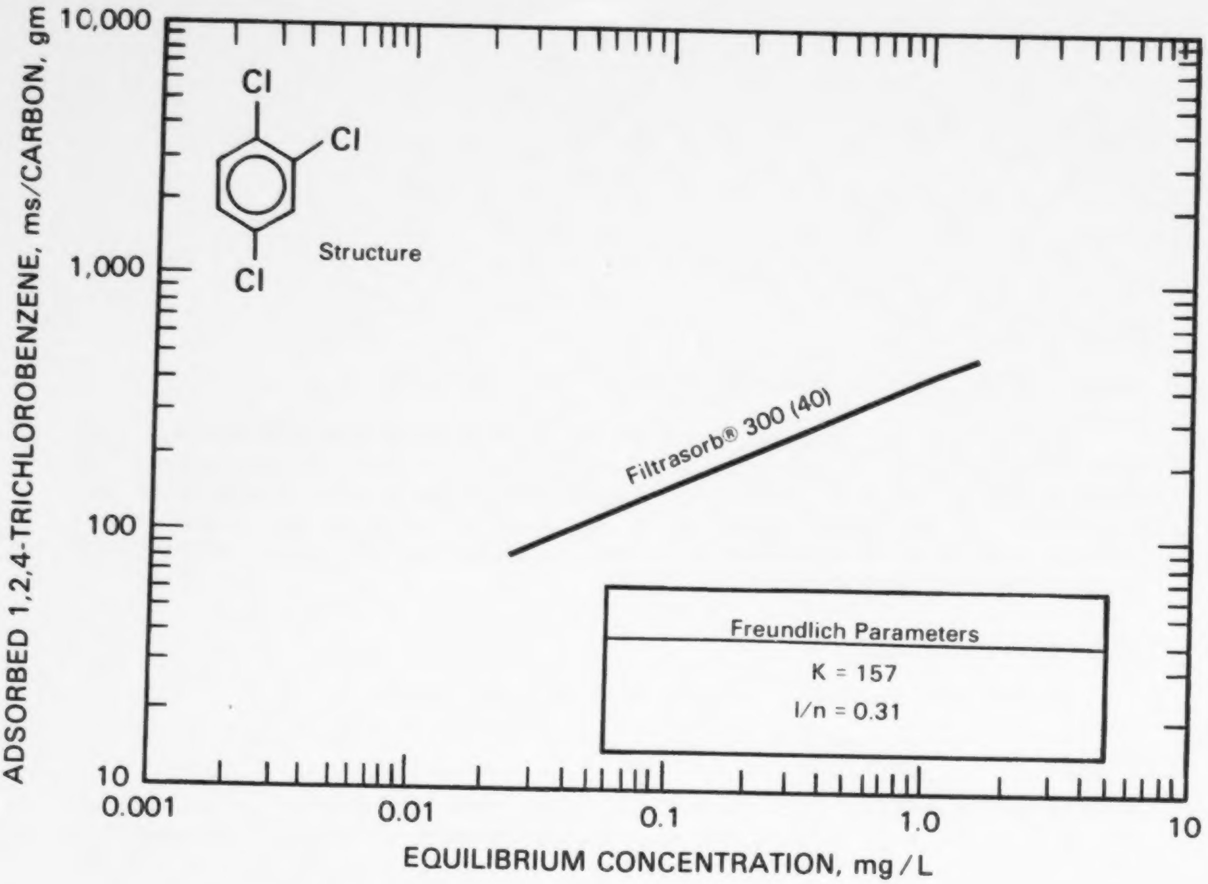


Figure 21. Isotherm for 1,2,4-Trichlorobenzene Adsorption on Activated Carbon.

SECTION 4

DISCUSSION OF TREATMENT ALTERNATIVES

CONVENTIONAL TREATMENT

In full-scale water treatment plants, tetrachloroethylene (7), cis-1,2-dichloroethylene (48), 1,2-dichloroethane (35, 58), carbon tetrachloride, and chlorobenzene (65) were not removed by coagulation, sedimentation, and filtration. In a study during which 1,2- and 1,4-dichlorobenzene and 1,2,4-trichlorobenzene were found in the raw waters of four full-scale treatment plants, they were also found in the finished waters at concentrations within the analytical variation of those in the raw waters. It can therefore be concluded that conventional treatment was ineffective for their control (65). It is unlikely, therefore, that other chloroethylenes, -ethanes, -methanes, and -benzenes would be effectively controlled by conventional treatment.

AERATION

Laboratory and field experimentation demonstrated that air stripping is a means for lowering the concentration of most of these contaminants in drinking water. In a USEPA Drinking Water Research Division experiment, tap water samples were spiked with trichloroethylene and tetrachloroethylene alone and in combination, and then they were aerated. No significant difference was observed in the removal efficiency of the individual solvents, whether they were alone or combined. This is important because mixtures of solvents exist in contaminated water and even though the effectiveness of the process varies for each solvent, aerating to remove one specific contaminant will also reduce the concentration of the others. A good example of this is given in Table 12. Although aeration was employed to remove tetrachloroethylene, the concentrations of the other solvents were also reduced. In this illustration, if the concentrations are simply added, the water contains approximately 460 μg/L of volatile organics before aeration and 40 μg/L afterwards, for about 92 percent overall removal efficiency.

Henry's Law Constant is useful in estimating whether or not aeration should be considered (24). The removal of a contaminant by aeration generally increases with Henry's Law Constant (Table 12). Thus, although no empirical data were available for control of many of these volatile compounds with aeration, the summary presentation of the constants in Figure 22 suggests the relative ease by which they might be removed by air stripping. Figures 23 to 26 compare available empirical data with a theoretical optimum removal developed by using the reciprocal of the Henry's Law Constants given in Reference 22. An explanation of this concept is given in Reference 67.

TABLE 12. EFFECTS OF AERATION ON A SOLVENT-CONTAMINATED GROUND WATER[*]

Contaminant	Average concentration, μg/L		Percent removal	Henry's Law Constant
	Before aeration	After aeration[†]		
1,1-Dichloroethylene	122	4	97	7.8 (22)
1,1,1-Trichloroethane	237	23	90	1.2 (22)
Tetrachloroethylene	94	9	90	1.1 (21, 22)
Trichloroethylene	3	0.4	87	0.5 (21, 22)
cis-1,2-Dichloroethylene	0.5	<0.1	>80	0.31 (22)
1,1-Dichloroethane	6	1	83	0.24 (22)
1,2-Dichloroethane	1.4	0.8	42	0.05 (21, 22)

[*] USEPA Drinking Water Research Division study in New Jersey.
[†] Diffused-air aeration, 10-minute contact: 4:1 (volume) air-to-water; Water depth = 0.8m.

Whether or not the exhaust gasses create a problem with aeration has been questioned. In one USEPA-DWRD sponsored aeration project, the principal investigator sampled for volatile solvents in the air near the top of the aerator and identified trichloroethylene, tetrachloroethylene, 1,1,1-trichloroethene, and 1,2-dichloroethane. The mean concentrations were far below allowable occupational exposures (68). This air sampling program is continuing, but the likelihood of creating an air pollution problem by aerating solvent contaminated drinking water is remote given existing air quality standards. Another topic of investigation by USEPA is the potential for water quality deterioration from air-borne particulates, oxidized inorganics, and microbiological growth in the aeration device. These are not thought to be significant problems, but are currently (1982) being investigated to more fully understand the aeration process.

ADSORPTION

Like aeration, adsorption has a spectrum of effectiveness. This proc-

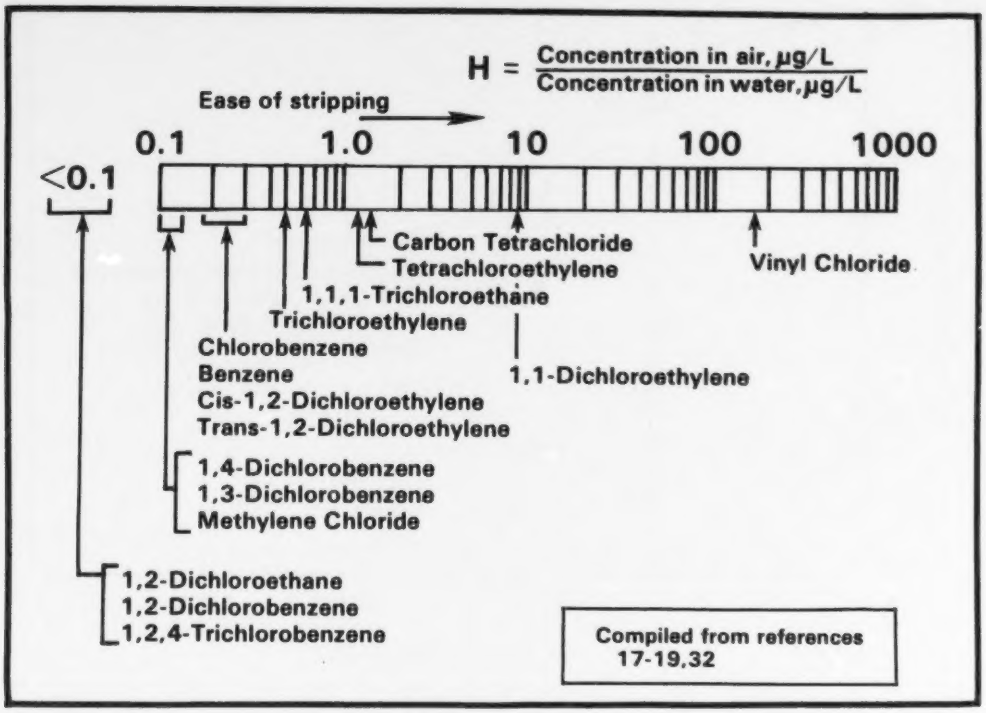
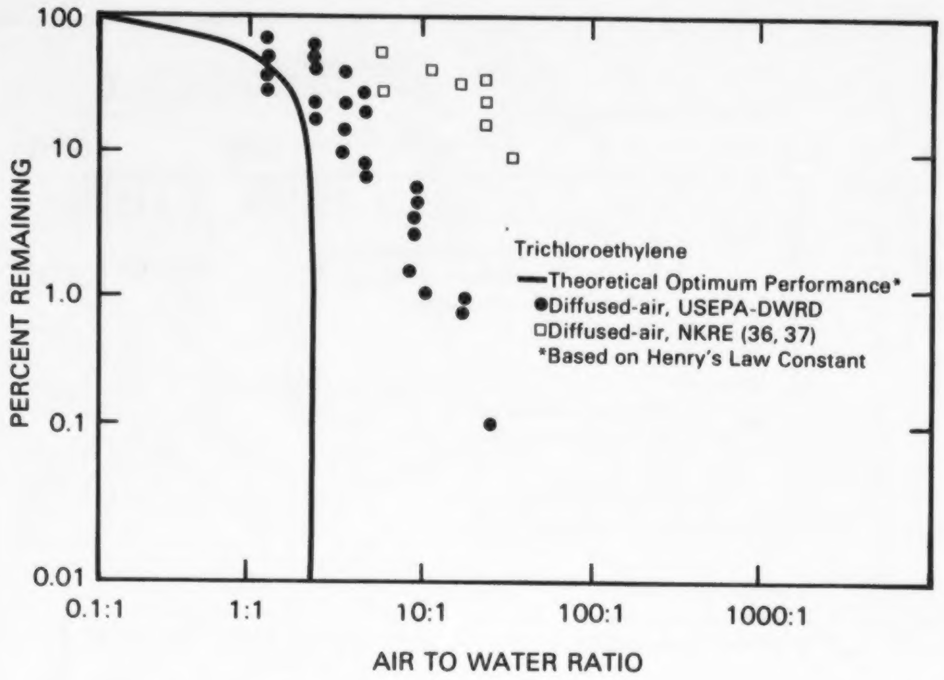


Figure 22. Comparison of Henry's Law Constants for Selected Organics.



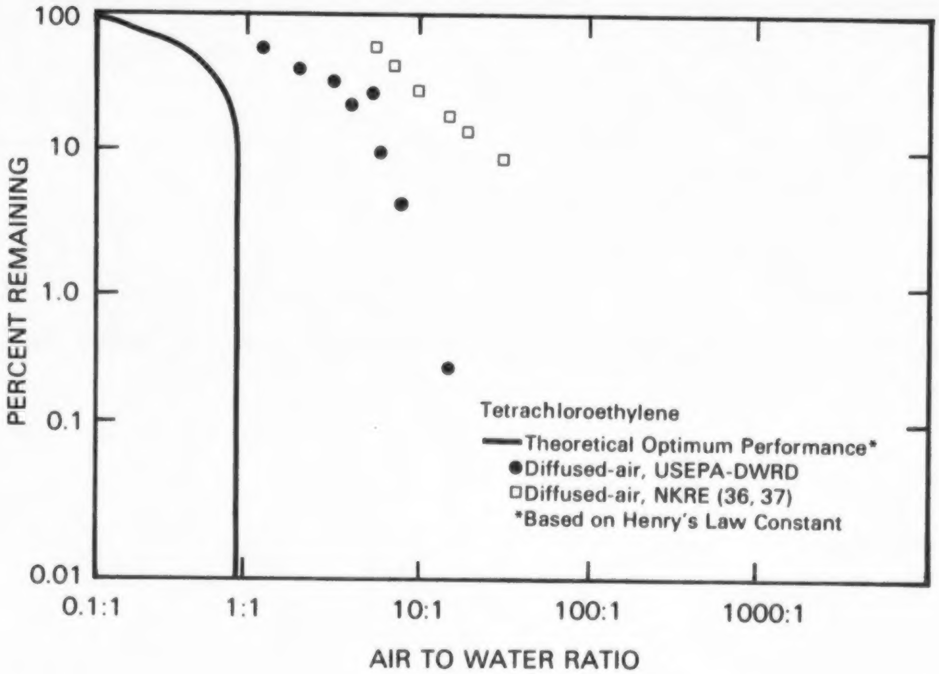


Figure 23. Comparison of Actual and Theoretical Removal of Trichloroethylene and Tetrachloroethylene from Drinking Water by Aeration.

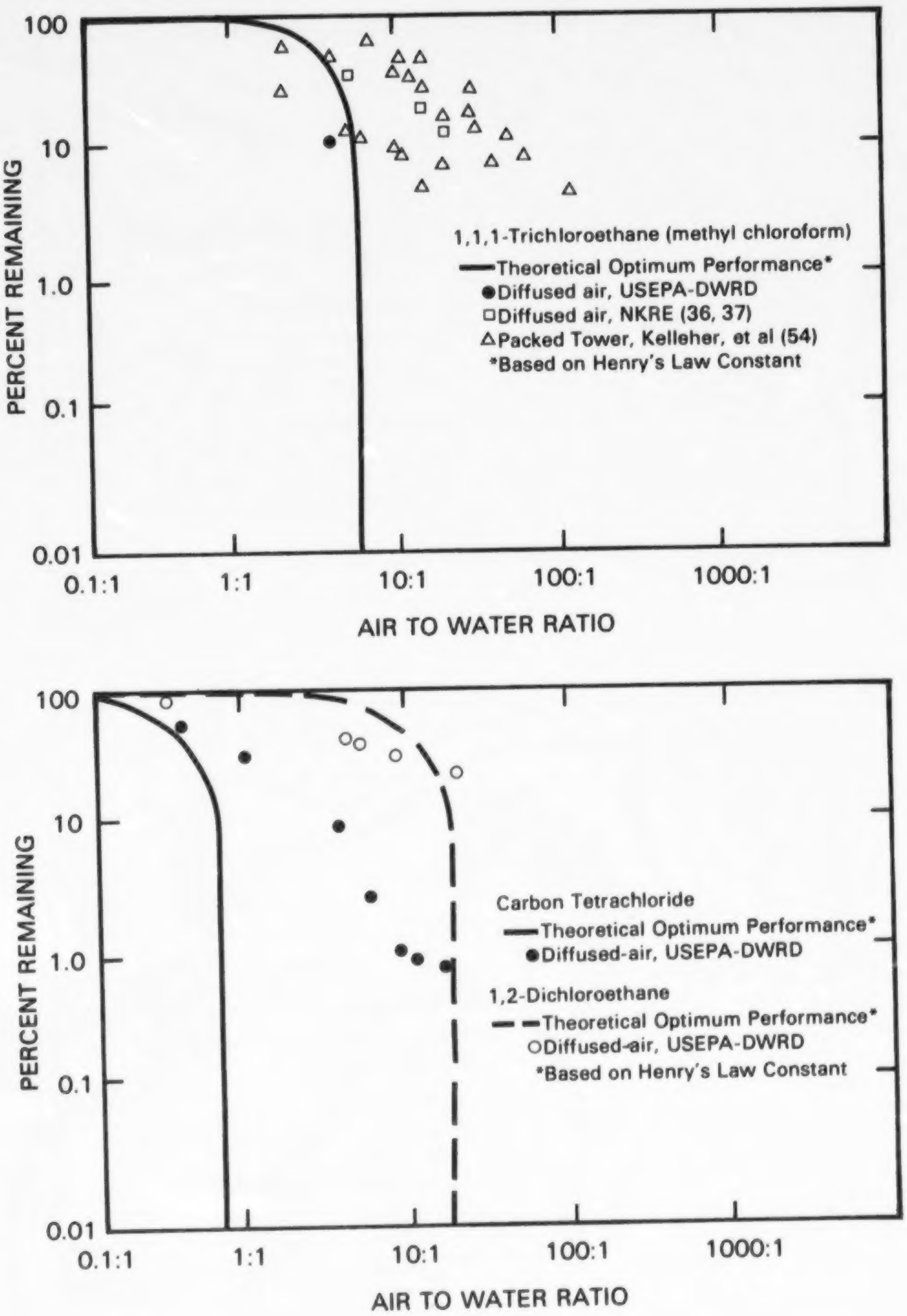
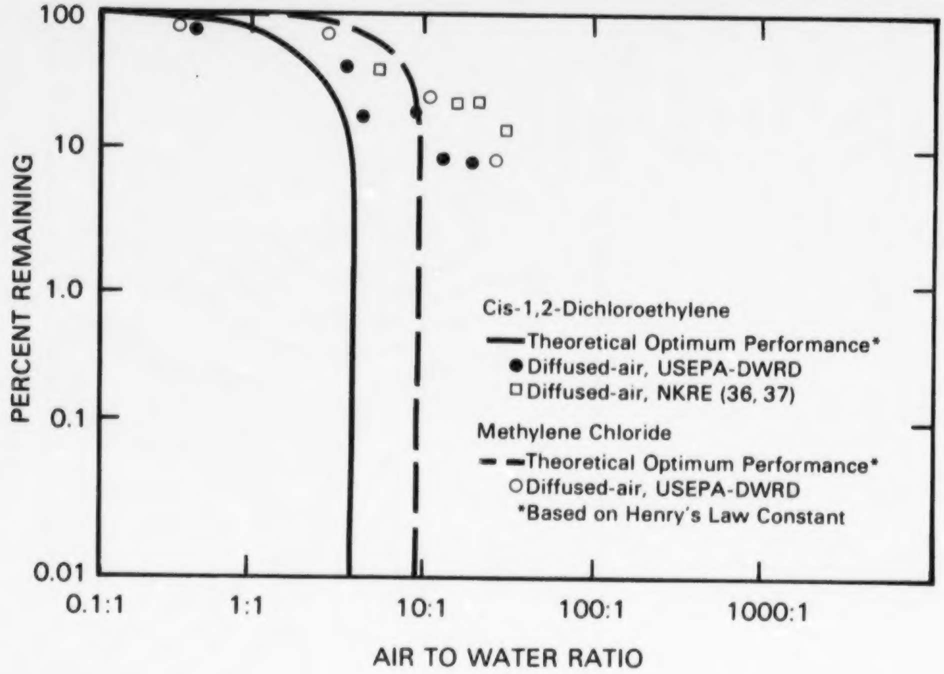


Figure 24. Comparison of Actual and Theoretical Removal of 1,1,1-Trichloroethane, Carbon Tetrachloride, and 1,2-Dichloroethane from Drinking Water by Aeration.



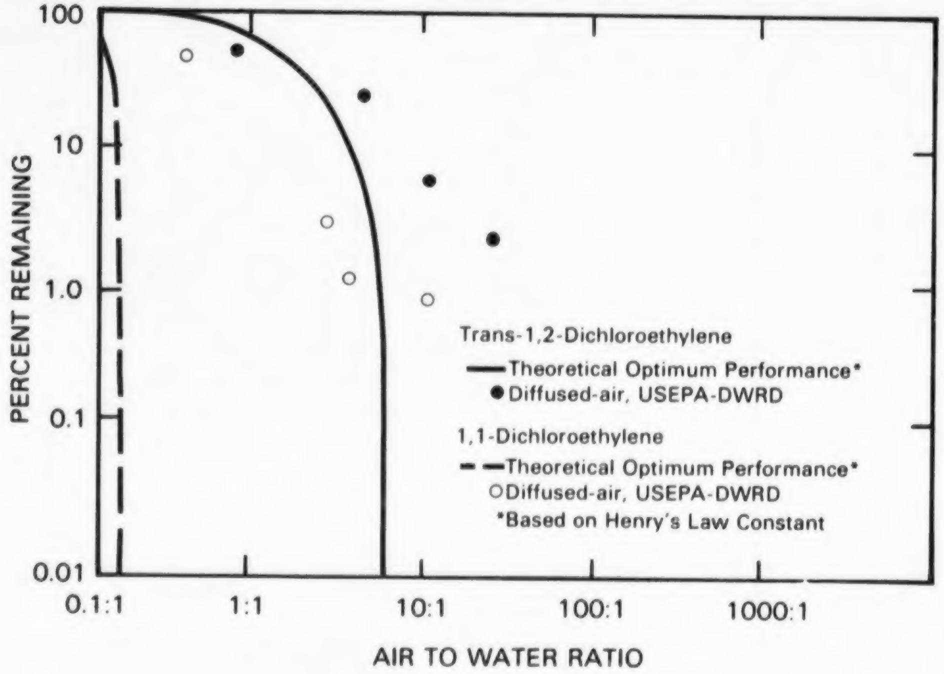


Figure 25. Comparison of Actual and Theoretical Removal of Cis- and Trans-1,2-Dichloroethylene, Methylene Chloride, and 1,1-Dichloroethylene from Drinking Water by Aeration.

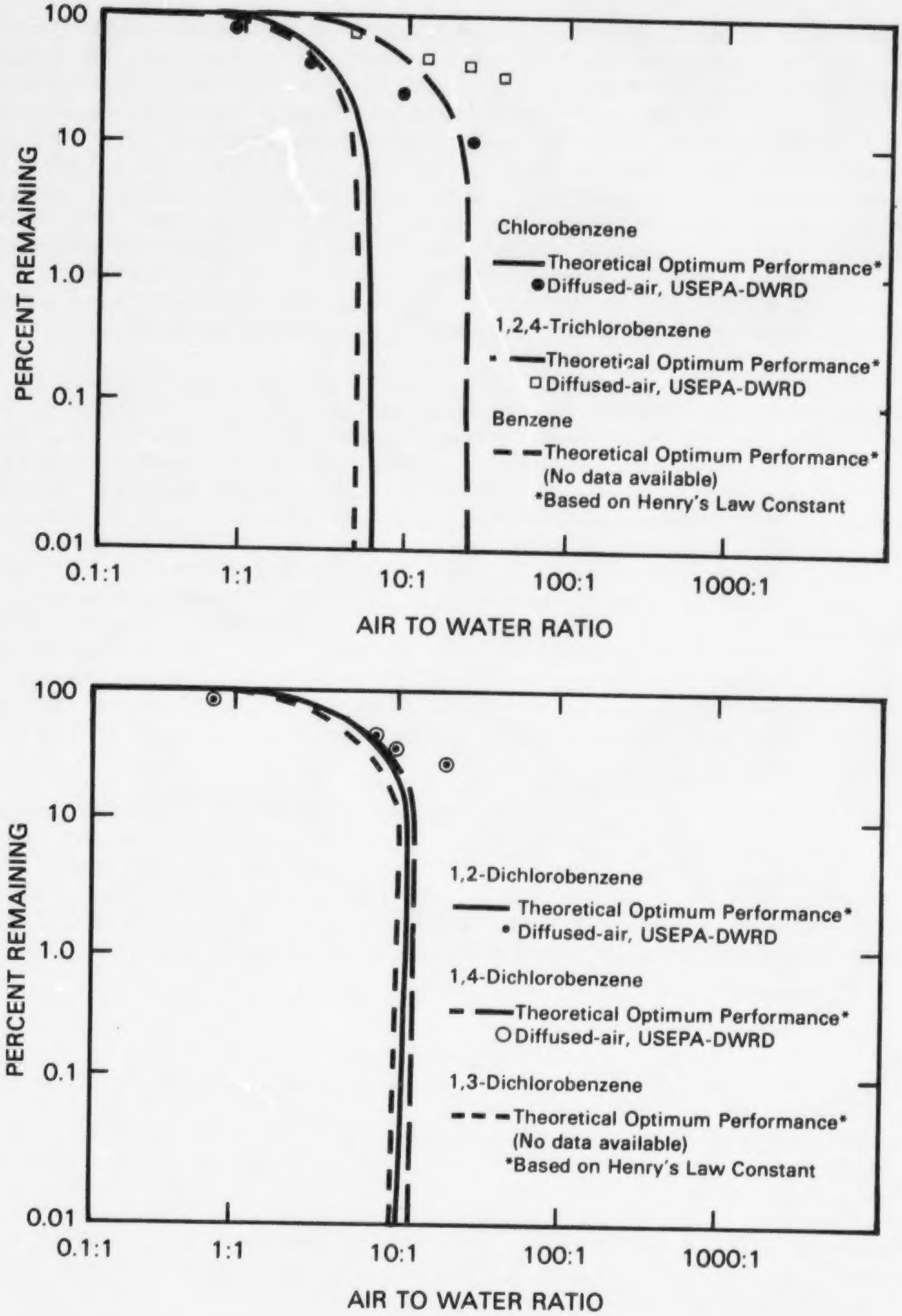


Figure 26. Comparison of Actual and Theoretical Removal of Benzene, Chlorobenzene, 1,2-, 1,3-, and 1,4-Dichlorobenzene, and 1,2,4-Trichlorobenzene from Drinking Water by Aeration.

ess, however, is more complicated than aeration and water quality can have a definite influence on performance. Figure 27 summarizes the data from several adsorption isotherm studies and for purposes of illustration, the adsorption capacity for each contaminant is shown at an equilibrium concentration of 500 μg/L. Table 13 incorporates this isotherm data with available empirical data (mostly from pilot scale studies), so actual can be compared to theoretical loadings. Note, even though the isotherm capacities represent pure compound adsorption without competition, and the empirical capacities represent adsorption in competition with background organics, in most cases, the actual loadings are higher than the isotherm predicts. This was unexpected, and the difference is perhaps the result of biodegradation or perhaps suggests a need for revision in isotherm procedures.

Concern has been expressed about having contaminants concentrate on an adsorbent then subsequently be released abruptly because of changing conditions. This has not been experienced. Researchers (8, 37, 48, 51, 62, 63, and others) have observed, however, periods when the effluent concentrations of an organic can exceed its influent value after passing through an adsorbent. This phenomenon is not apparent in Figure 28, where the organic concentrations are simply added together to assess overall performance, but some desorption is occurring when individual organic behavior is examined. Note Figure 12 after week 50 on the unaerated flow stream in New Jersey and between weeks 40 and 50 in Connecticut. In these examples, the concentration of 1,1,1-trichloroethane in the effluent from the activated carbon adsorber is higher than in the influent, but like others have observed, this occurs when the influent concentration of adsorbate declines and the resulting desorption or "leakage" can be explained by adsorption equilibrium theory.

The synthetic resin, Ambersorb® XE-340 looked very promising because it had a high capacity for most of these contaminants (Table 14). Field data indicated that the resin's capacity was typically two to three times that of activated carbon (on a weight basis) for control to breakthrough. Recently (1982), however, the manufacturer announced that this resin would not be produced commercially, so the future of adsorption by synthetic resins is questionable.

BOILING

Boiling is oftentimes suggested as a means for consumers to decontaminate drinking water. Five minutes of vigorous boiling in shallow open vessels has been shown to remove an average of 99 percent or more of trichloroethylene, tetrachloroethylene, 1,1,1-trichloroethane, and carbon tetrachloride (44, 57), whose boiling points or azeotropic boiling points are below that of water. The Drinking Water Research Division developed a boiling protocol* to compare relative efficiencies of removal. This laboratory data is summarized in Table 15 and in general, the spectrum of removal (i.e. the most easily removed group to the most difficult) is:

Chloroethylenes > chloroethanes > aromatic hydrocarbons > halobenzenes

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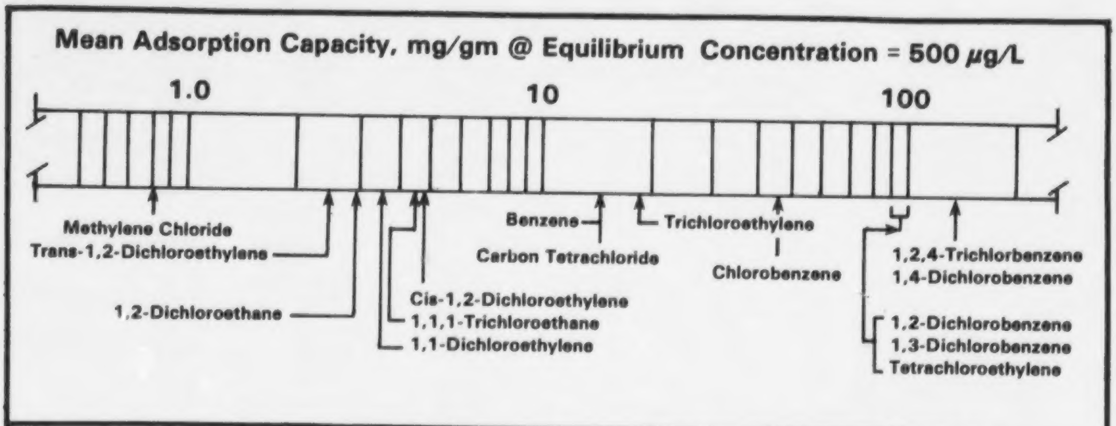
*Details on this procedure are available from the authors.



	Freundlich Parameters	
	K	l/n
Benzene	1.0	1.6*
	16.6	0.4**
	49.3	0.6†
	29.5	0.4††
	14.2	0.4§
Carbon Tetrachloride	11.1	0.8*
	28.5	0.8†
	38.1	0.7**
	25.8	0.7††
	14.2	0.7§
	14.8	0.4§§
Chlorobenzene	91.0	1.0*
1,2-dichlorobenzene	129.0	0.4*
1,3-dichlorobenzene	118.0	0.4*
1,4-dichlorobenzene	121.0	0.5*
	226.0	0.4**
1,2-dichloroethane	3.6	0.8*
	5.7	0.5§§
cis-1,2-dichloroethylene	8.4	0.5§§
	6.5	0.7‡

	Freundlich Parameters	
	K	l/n
trans-1,2-dichloroethylene	3.1	0.5*
1,1-dichloroethylene	4.9	0.5*
Methylene chloride	1.3	1.2*
	1.6	0.7***
Tetrachloroethylene	50.8	0.6*
	84.1	0.4§§
	273.0	0.6***
1,2,4-trichlorobenzene	157.0	0.3*
1,1,1-trichloroethane	2.5	0.3*
	9.4	0.5§§
Trichloroethylene	28.0	0.6*
	26.2	0.5‡
	28.2	0.4§§
Vinyl chloride	Not Reported	

Freundlich equation:
$x/m(mg/gm) = K\ C_e(mg/l)^{l/n}$

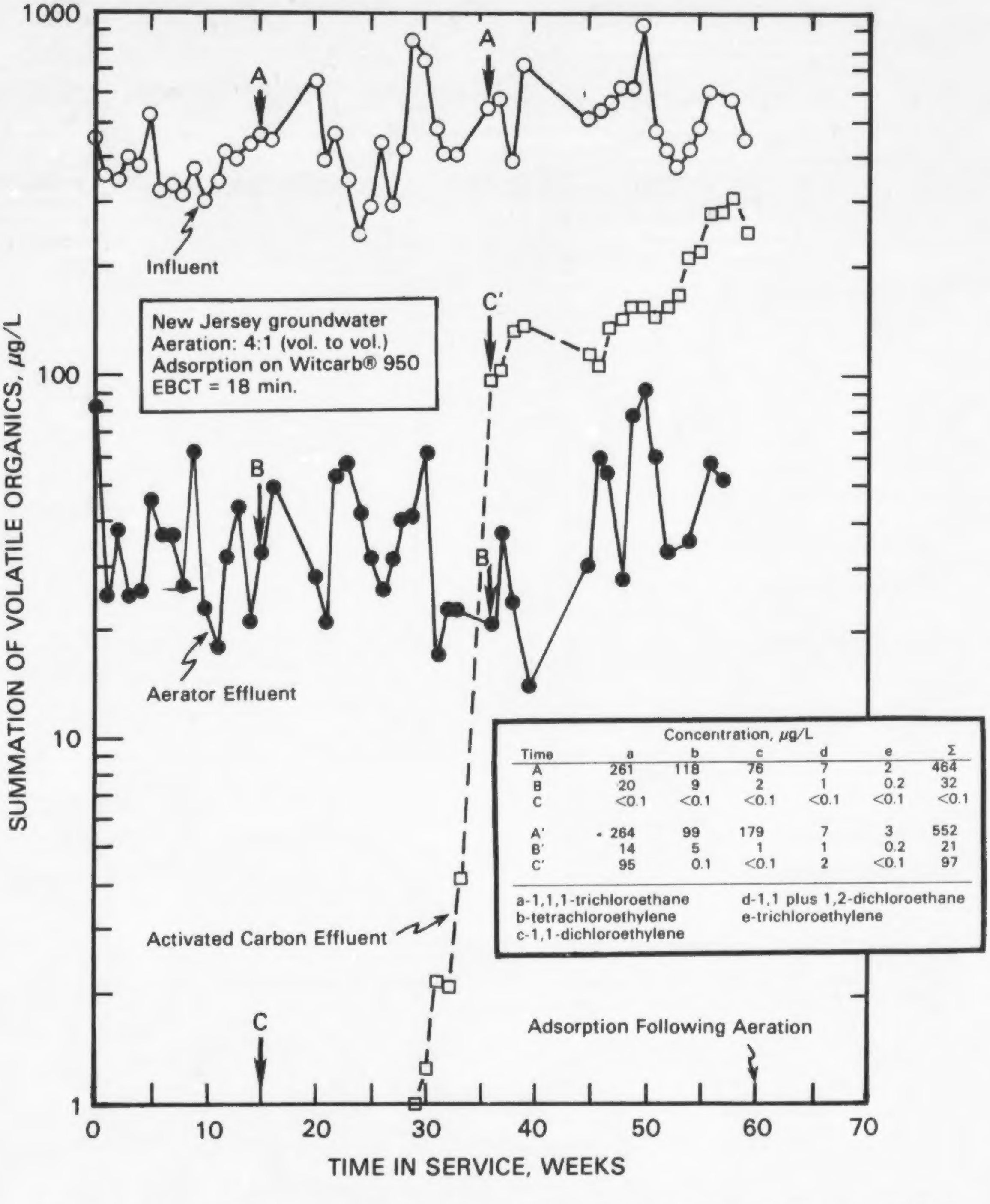
*Filtrasorb® 300(40)
**Filtrasorb® 400(62)
***Filtrasorb® 400(47)
§Hydrodarco® 1030 (62)
§§Witcarb® 950
†Norit(62)
††Nuchar® WV-G(62)
‡Filtrasorb® 300

Figure 27. Comparison of Isotherm Adsorption Capacities on Activated Carbon.

TABLE 13. ADSORPTION OF VOLATILE ORGANIC COMPOUNDS BY GRANULAR ACTIVATED CARBON, SUMMARY

	Avg. conc., μg/L	Bed depth, m (ft)	EBCT, min	Loading, m^3/m^3(a)		Exhaustion capacity, m^3/m^3 (b)	Reference
				Breakthrough 0.1 μg/L (except as noted)	Exhaustion (inf = eff)		
Trichloroethylene	177	0.8 (2.5)	9	>20,160	>20,160	21,500	USEPA-DWRD
	4	0.8 (2.5)	8.5	>60,900 but <123,340	>123,340	99,900	"
	3*	0.8 (2.5)	18	>32,500	>32,500	106,560	"
	0.4**	0.8 (2.5)	18	>32,500	>32,500	199,800	"
Tetrachloroethylene	1400	0.8 (2.5)	9	12,300	33,100	17,500	USEPA-DWRD
	94*	0.8 (2.5)	18	>32,500	>32,500	57,400	"
	9**	0.8 (2.5)	18	>32,500	>32.500	162,800	"
	4	0.8 (2.5)	8.5	>60,900 but <123,340	>123,340	237,600	"
	1	0.8 (2.5)	9	>20,160	>20,160	475,200	"
1,1,1-Trichloroethane	100	0.6 (2)	7.5	1,300†	not reported	3,800	(54)
		1.2 (4)	15	2,700†	not reported	3,800	"
		1.8 (6)	22.5	3,900†	not reported	3,800	"
	237*	0.8 (2.5)	18	15,700	30,800	2,600	USEPA-DWRD
	23**	0.8 (2.5)	18	>32,500	>32,500	12,000	"
	38	0.8 (2.5)	8.5	11,800	26,000	9,400	"
	1	0.8 (2.5)	9	16,400	22,500	94,400	"
Carbon Tetrachloride	12	0.8 (2.5)	10	14,000	25,000	9,400	(63)
		0.8 (2.5)	5	6,050	not reported	9,400	"
Cis-1,2-Dichloroethylene‡	18	0.8 (2.5)	6	4,100	15,800	9,400	(48)
		1.5 (5)	12	7,100	14,300	9,400	"
		2.3 (7.5)	18	8,100	13,700	9,400	"
	6	0.8 (2.5)	9	14,200	19,000	15,300	USEPA-DWRD
	2	0.8 (2.5)	8.5	29,600	48,600	26,000	"
Vinyl Chloride	7	0.8 (2.5)	6	810	2,400	Isotherm not reported	(48)
		1.5 (5)	12	1,250	-		"
		2.3 (7.5)	18	2,800	-		"
		3.1 (10)	25	2,050	5,011		"
1,2-Dichloroethane	8	0.8 (2.5)	20	1,700	8,640	3,500	(58)
	1.4*	0.8 (2.5)	18	17,400	45,900	5,700	USEPA-DWRD
	0.8**	0.8 (2.5)	18	>32,500	>32,500	5,000	"
	2	0.9 (3)	11	3,300	9,160	4,000	(35)
		1.8 (6)	22	3,400	7,850	4,000	"
		2.7 (9)	33	4,150	>7,000	4,000	"
		3.6 (12)	44	>7,000	>7,000	4,000	"
		0.8 (2.5)	17.5	2,500	7,450	4,000	"
		0.7 (2.4)	17	2,500	7,450	4,000	"
1,1-Dichloroethylene	122*	0.8 (2.5)	18	22,400	>33,600	5,600	USEPA-DWRD
	4**	0.8 (2.5)	18	>33,600	>33,600	31,100	"
Benzene	5000	2.9 (9.4)	54	3,030@	>3,030	4,100	(64)
Methylene Chloride	20,000	2.7 (8.8)	262	860	860	600	(64)

(a) m^3 water/m^3 carbon
(b) Predicted by Freundlich isotherms. Reference 40.
* Adsorption of unaerated water; ** Adsorption after 10-minute aeration @ 4:1 (volume) air-to-water
† 5 μg/L in effluent; @ 10 μg/L in effluent
‡ Isotherm capacities based on Reference 40 trans-1, 2-dichloroethylene



Time	a	b	c	d	e	Σ
	Concentration, μg/L					
A	261	118	76	7	2	464
B	20	9	2	1	0.2	32
C	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
A′	264	99	179	7	3	552
B′	14	5	1	1	0.2	21
C′	95	0.1	<0.1	2	<0.1	97

a-1,1,1-trichloroethane
b-tetrachloroethylene
c-1,1-dichloroethylene
d-1,1 plus 1,2-dichloroethane
e-trichloroethylene

Figure 28. Removal of Volatile Organic Compounds by Aeration and Adsorption on Granular Activated Carbon (Pilot Scale Study).

TABLE 14. ADSORPTION OF TRICHLOROETHYLENE AND RELATED SOLVENTS BY AMBERSORB® XE-340, SUMMARY

	Avg. conc, μg/L	Bed depth, m (ft)	Empty bed contact time, minutes	Loading to 0.1 μg/L breakthrough, m³/m³*	Reference
Trichloroethylene	215	0.3 (1)	2	83,700**	37
	210	0.6 (2)	4	78,600**	"
	210	1.2 (4)	7.5	>53,300**	"
	177	0.8 (2.5)	9	>20,160	8
	4	0.8 (2.5)	8.5	>123,340	USEPA-DWRD
	3	0.2 (0.8)	5	>117,000	"
Tetrachloroethylene	41	0.3 (1)	2	>99,900**	37
	51	0.6 (2)	4	78,600**	"
	65	1.2 (4)	7.5	>53,300**	"
	70	0.3 (1)	2	106,000**	"
	94	0.8 (2.5)	5	112,900	USEPA-DWRD
	1400	0.8 (2.5)	9	17,920	"
	3	0.8 (2.5)	8.5	>123,340	"
	2	0.8 (2.5)	9	>20,160	8
1,1,1-Trichloroethane	5	1.2 (4)	7.5	39,300**	37
	33	0.8 (2.5)	9	56,000	8
	237	0.2 (0.8)	5	82,600	USEPA-DWRD
	23	0.2 (0.8)	5	>100,800	"
	1	0.8 (2.5)	9	>20,160	8
Carbon Tetrachloride	19	0.8 (2.5)	5	7560	8
	19	0.8 (2.5)	10	15,120	8
Cis-1,2-Dichloroethylene	40	0.3 (1)	2	37,200**	37
	38	0.6 (2)	4	39,500**	"
	40	1.2 (4)	7.5	19,700**	"
	40	0.3 (1)	2	36,400**	"
	25	0.8 (2.5)	6	14,400	48
	22	0.8 (2.5)	6	7200	"
	16	0.8 (2.5)	6	11,500	"
	6	0.8 (2.5)	9	>20,160	8
	2	0.8 (2.5)	8.5	>59,000 but<123,340	USEPA-DWRD
1,2-Dichloroethane	1	0.2 (0.8)	5	108,860	USEPA-DWRD
1,1-Dichloroethylene	122	0.2 (0.8)	5	80,600	USEPA-DWRD
	4	0.2 (0.8)	5	110,800	"

*m³ water/m³ carbon

**Breakthrough defined by shape of wavefront curve; generally 20 to 25 μg/L of contaminant in adsorbent effluent

TABLE 15. REMOVAL OF VOLATILE ORGANIC COMPOUNDS FROM DRINKING WATER BY BOILING, SUMMARY

	Percent Remaining*						
	Time of boiling, min.						
Organic Compound	1	2	3	4	5	10	15
Trichloroethylene	18	10	5	2	0.7	< 0.1	< 0.1
Tetrachloroethylene	14	8	4	2	0.8	< 0.1	< 0.1
Cis-1,2-Dichloroethylene	24	14	8	5	2	< 0.1	< 0.1
Trans-1,2-Dichloroethylene	14	9	1	< 0.1	< 0.1	< 0.1	< 0.1
1,1-Dichloroethylene	10	6	3	0.9	0.2	< 0.1	< 0.1
Vinyl chloride		-----	No	data	available		-----
1,1,1-Trichloroethane	16	8	4	1	1	< 0.1	< 0.1
1,2-Dichloroethane	39	31	24	16	12	2	0.1
Carbon Tetrachloride	13	7	3	1	0.5	< 0.1	< 0.1
Methylene chloride	28	20	13	8	5	0.3	< 0.1
Benzene	33	26	18	14	10	0.9	< 0.1
Chlorobenzene	31	22	13	8	5	< 0.1	< 0.1
1,2-Dichlorobenzene	38	28	21	16	14	2	< 0.1
1,3-Dichlorobenzene	29	20	13	8	5	< 0.1	< 0.1
1,4-Dichlorobenzene	42	34	26	20	17	10	6
1,2,4-Trichlorobenzene	39	31	23	17	12	2	0.8

*Initial concentrations ranged from 88 to 1900 μg/l

SECTION 5

ESTIMATED TREATMENT COSTS

In any economic analysis, the cost data presented are dependent on the particular design assumptions made for the treatment system. For example, the costs associated with aeration are quite sensitive to the removal efficiencies. The cost of treatment, therefore, can vary significantly depending on the design parameters selected by the cost analyst and on site-specific considerations. For this reason, these cost estimates should be viewed as a preliminary attempt to quantify the economics of removing volatile organic chemicals, such as trichloroethylene and related solvents, from drinking water.

The first step is to estimate the cost required in developing a treatment matrix. Influent concentrations were selected, and the treatment necessary to achieve hypothetical effluent qualities* was then determined. For aeration, air-to-water ratios were estimated (Table 15) by developing an envelope around the empirical data in Figures 23, 24, and 25, and extrapolating for the higher removal efficiencies.

Estimating the activated carbon usage necessary to achieve hypothetical target levels (Table 16) was more complicated. First, two ratios were established for each contaminant: a) capacity at exhaustion observed from field studies divided by theoretical capacity determined from Dobbs' and Cohen's (40) isotherm data and b) capacity at actual exhaustion divided by capacity at actual breakthrough (Table 13). Isotherm capacities at the given contaminant concentrations (1000, 100, 10, and 1 μg/L) were then multiplied by ratio "a" to give an estimated activated carbon usage to exhaustion, and that value was then divided by ratio "b" to give an estimated activated carbon usage to breakthrough. Carbon usage for intermediate effluent concentrations were then estimated from a semilog plot (Figure 29).

The ranges of estimated aeration requirements and activated carbon usage shown in Tables 15 and 16 are extremely wide for certain contaminant concentrations, so on-site, pilot scale experimentation would be prudent if treatment by either process is contemplated. For this purpose, however, it does allow some preliminary estimates of treatment costs using computer cost programs developed by Gumerman and others (69).

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*Maximum contaminant levels have not been established for these organic compounds. However, the USEPA Office of Drinking Water has developed "Health Advisories" and has suggested (1) possible ranges for lifetime exposure to selected organic chemicals.

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TABLE 16. ESTIMATED AIR-TO-WATER RATIOS NECESSARY TO ACHIEVE DESIRED TREATMENT, SUMMARY

	Inf. conc., µg/L	Effluent concentration, µg/L														
		0.1			1			10			50			100		
		a	b	c	a	b	c	a	b	c	a	b	c	a	b	c
Trichloroethylene	1000	2:1	40-136:1	76:1	2:1	25-100:1	54:1	2:1	10-66:1	32:1	2:1	4-44:1	17:1	2:1	3-34:1	11:1
	100	2:1	25-100:1	54:1	2:1	10-66:1	32:1	2:1	3-34:1	11:1	<1:1	1-10:1	1:1	<1:1	-	-
	10	2:1	10-66:1	32:1	2:1	3-34:1	11:1	-	-	-	-	-	-	-	-	-
	1	2:1	3-34:1	11:1	-	-	-	-	-	-	-	-	-	-	-	-
Tetrachloroethylene	1000	1:1	25-320:1	96:1	1:1	17-150:1	72:1	<1:1	11-65:1	45:1	<1:1	8-36:1	26:1	<1:1	6-30:1	18:1
	100	1:1	17-150:1	72:1	1:1	11-65:1	45:1	<1:1	6-30:1	18:1	<1:1	2-7:1	1:1	-	-	-
	10	1:1	11-65:1	45:1	1:1	6-30:1	18:1	-	-	-	-	-	-	-	-	-
	1	1:1	6-30:1	18:1	-	-	-	-	-	-	-	-	-	-	-	-
1,1,1-Trichloroethane	1000	6:1	60-600:1	198:1	6:1	21-260:1	90:1	6:1	10-120:1	35:1	6:1	5-65:1	14:1	6:1	4-52:1	8:1
	100	6:1	21-260:1	90:1	6:1	10-120:1	35:1	6:1	4-52:1	8:1	4:1	1-15:1	1:1	-	-	-
	10	6:1	10-120:1	35:1	6:1	4-52:1	8:1	-	-	-	-	-	-	-	-	-
	1	6:1	4-52:1	8:1	-	-	-	-	-	-	-	-	-	-	-	-
Carbon tetrachloride	1000	1:1	-	19:1	1:1	-	15:1	1:1	-	10:1	1:1	-	6:1	<1:1	-	4:1
	100	1:1	-	15:1	1:1	-	10:1	1:1	-	6:1	<1:1	-	1:1	-	-	-
	10	1:1	-	10:1	1:1	-	6:1	-	-	-	-	-	-	-	-	-
	1	1:1	-	6:1	-	-	-	-	-	-	-	-	-	-	-	-
Cis-1,2-Dichloroethylene	1000	4:1	14-152:1	104:1	9:1	10-115:1	77:1	4:1	8-76:1	52:1	4:1	5-50:1	34:1	4:1	4-38:1	26:1
	100	4:1	10-115:1	77:1	4:1	8-76:1	52:1	4:1	4-38:1	26:1	2:1	2-10:1	4:1	-	-	-
	10	4:1	8-76:1	52:1	3:1	4-38:1	26:1	-	-	-	-	-	-	-	-	-
	1	3:1	4-38:1	26:1	-	-	-	-	-	-	-	-	-	-	-	-
1,2-Dichloroethane	1000	20:1	-	56:1	20:1	-	42:1	20:1	-	28:1	20:1	-	18:1	-	-	14:1
	100	20:1	-	42:1	20:1	-	28:1	18:1	-	14:1	10:1	-	-	-	-	-
	10	20:1	-	28:1	18:1	-	14:1	-	-	-	-	-	-	-	-	-
	1	18:1	-	14:1	-	-	-	-	-	-	-	-	-	-	-	-
1,1-Dichloroethylene	1000	0.1:1	-	10:1	0.1:1	-	8:1	0.1:1	-	5:1	0.1:1	-	3:1	<0.1:1	-	3:1
	100	0.1:1	-	8:1	0.1:1	-	5:1	<0.1:1	-	3:1	-	-	-	-	-	-
	10	0.1:1	-	5:1	<0.1:1	-	3:1	-	-	-	-	-	-	-	-	-
	1	<0.1:1	-	3:1	-	-	-	-	-	-	-	-	-	-	-	-

a = Theoretical optimum air-to-water ratio based on the reciprocal of the Henry's Law Constants given in Reference 22. An explanation of this concept is given in Reference 67. For vinyl chloride, this optimum value is <<0.1:1.

b = Range of air-to-water ratios extrapolated from actual experimentation. This is estimated by developing an envelope around the data in Figures 23, 24, and 25, for log % remaining vs. air-to-water ratio.

c = Average air-to-water ratio calculated from "b".

TABLE 17. ESTIMATED CARBON USAGE NECESSARY TO ACHIEVE DESIRED TREATMENT, SUMMARY

	Inf. conc., µg/L	Desired effluent concentration, µg/L									
		0.1		1		10		50		100	
		a	b	a	b	a	b	a	b	a	b
Trichloro-ethylene	1000	5.7-10.5	6.9 (0.50)	7.8-11.3	8.7 (0.4)	9.8-12.2	10.4 (0.32)	11.2-12.7	11.6 (0.29)	11.8-13.0	12.1 (0.28)
	100	13.8-25.3	16.7 (0.20)	20.2-27.9	22.1 (0.15)	26.7-30.5	27.7 (0.12)	31.2-32.3	31.5 (0.11)	-	-
	10	33.1-64.6	41.0 (0.08)	56.3-72.1	60.3 (0.06)	-	-	-	-	-	-
	1	79.4-146	96.1 (0.03)	-	-	-	-	-	-	-	-
1,1,1-Trichloro-ethane	1000	0.17-6.1	1.7 (2.0)	0.19-7.5	2.6 (1.3)	0.2-8.9	3.3 (1.0)	0.21-9.9	3.9 (0.86)	0.22-10.3	4.2 (0.80)
	100	0.79-28.0	8.1 (0.41)	0.88-36.0	13.0 (0.26)	0.98-45.0	18.0 (0.19)	1.1-51.0	21.0 (0.16)	-	-
	10	3.6-127	37.0 (0.09)	4.3-186	70.0 (0.05)	-	-	-	-	-	-
	1	16.0-580	169 (0.02)	-	-	-	-	-	-	-	-
Tetrachloro-ethylene	1000	13.6-16.2	14.7 (0.23)	17.7-21.8	20.7 (0.16)	24.7-27.5	26.7 (0.13)	29.5-31.4	30.9 (0.11)	31.7-33.2	32.7 (0.10)
	100	29.2-44.4	40.1 (0.08)	55.0-66.7	59.6 (0.06)	80.6-83.8	81.2 (0.41)	99.0-101	100 (0.03)	-	-
	10	80.4-122	111 (0.03)	186-208	200 (0.02)	-	-	-	-	-	-
	1	221-337	306 (0.01)	-	-	-	-	-	-	-	-
Carbon tetra-chloride	1000	2.9-6.6	4.8 (0.7)	5.0-7.9	6.5 (0.51)	7.2-9.2	8.2 (0.41)	8.8-10.1	9.5 (0.35)	9.3-10.5	9.9 (0.34)
	100	4.3-9.8	7.0 (0.48)	8.8-12.3	10.6 (0.32)	13.2-14.8	14.0 (0.24)	16.1-16.6	16.3 (0.21)	-	-
	10	6.4-14.4	10.4 (0.32)	16-20.1	18.0 (0.19)	-	-	-	-	-	-
	1	9.5-21.4	15.5 (0.22)	-	-	-	-	-	-	-	-
Cis-1,2-Dichloro-ethylene	1000	0.6-1.4	1.1 (3.0)	1.0-1.6	1.3 (2.6)	1.4-1.9	1.5 (2.2)	1.4-2.0	1.7 (2.0)	1.5-2.1	1.8 (1.9)
	100	1.8-4.4	3.3 (1.0)	3.5-5.3	4.2 (0.8)	4.4-6.2	5.2 (0.65)	4.7-6.9	5.9 (0.55)	-	-
	10	5.5-13.5	10.1 (0.3)	13.0-17.8	14.6 (0.2)	-	-	-	-	-	-
	1	17.0-41.6	31.1 (0.1)	-	-	-	-	-	-	-	-
1,2-Dichloro-ethane	1000	0.8-5.2	2.0 (1.7)	1.3-7.0	3.1 (1.1)	1.7-9.0	4.1 (0.82)	2.0-11.1	4.9 (0.68)	2.2-12.0	5.2 (0.65)
	100	1.1-8.4	3.5 (1.0)	2.2-13.0	5.4 (0.62)	3.0-17.6	7.3 (0.46)	3.6-20.8	8.6 (0.39)	-	-
	10	1.6-12.5	5.2 (0.65)	3.8-22.6	9.3 (0.36)	-	-	-	-	-	-
	1	2.4-18.4	7.6 (0.45)	-	-	-	-	-	-	-	-
1,1-Dichloro-ethylene	1000	2.5-8.5	5.5 (0.61)	3.3-11.5	7.4 (0.45)	4.8-14.5	9.6 (0.36)	4.8-16.6	11.0 (0.31)	5.1-17.5	11.3 (0.29)
	100	7.1-24.6	15.9 (0.21)	10.4-36.4	23.0 (0.14)	13.8-47.7	30.8 (0.11)	16.1-55.7	35.9 (0.09)	-	-
	10	20.4-71	45 (0.07)	34.8-120	77.4 (0.04)	-	-	-	-	-	-
	1	59.0-205	132 (0.03)	-	-	-	-	-	-	-	-

a = Granular activated carbon loading range, 10^3 m^3 water/m^3 carbon, estimated from Reference 40 isotherms and empirical data in Table 15.

b = Mean loading, 10^3 m^3 water/m^3 carbon (GAC usage, lb carbon/10^3 gal water)

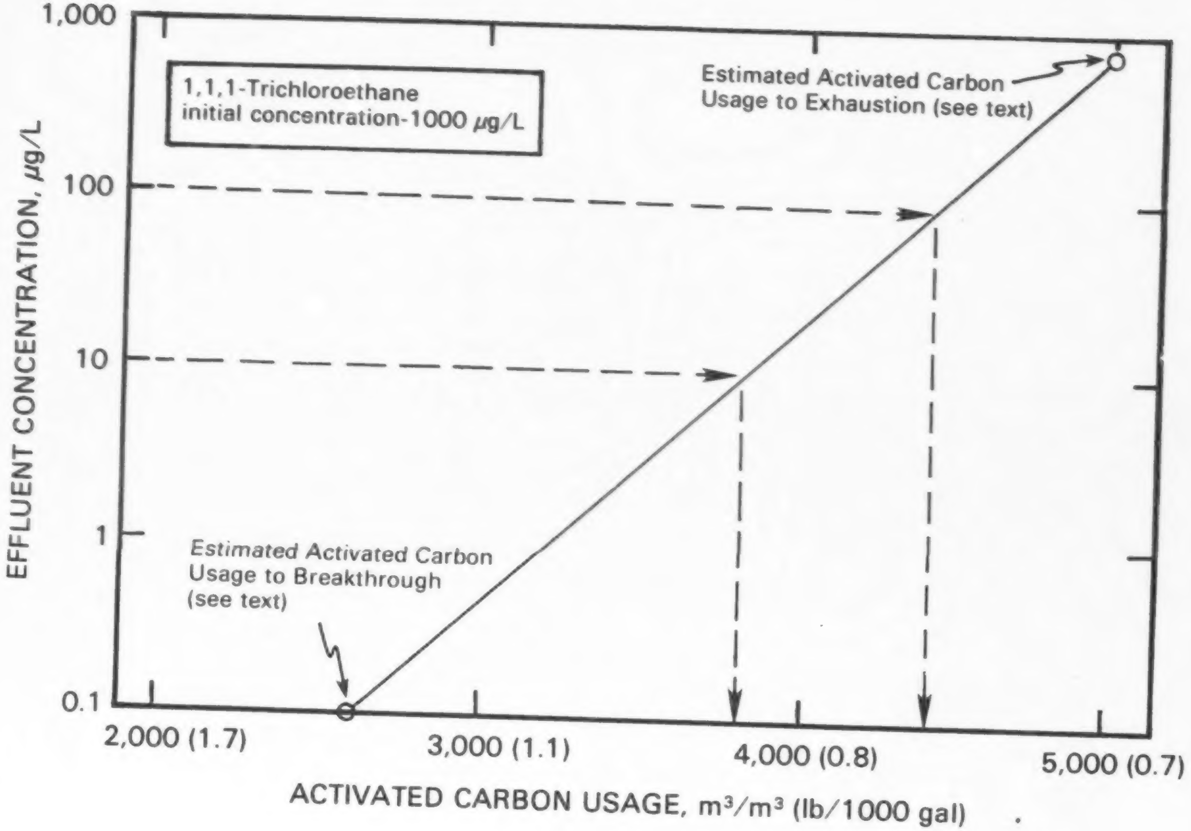

Figure 29. Estimated Activated Carbon Usage to Achieve Target Effluent Qualities.

The cost analysis is based on 1.3 m^3/min (500,000 gal/day) flow with the treatment system shown in Figure 30. The ground water is treated by tower aeration, diffused-air aeration, or granular activated carbon (GAC) followed by chlorination, clearwell storage, and high-lift pumping.

The aeration towers are rectangular with an overall height of 3 m (10 ft), and an air supply of 137 sLm/m^2 (52 scfm/ft^2) of surface area is assumed. They have electrically driven, induced-draft fans, fan stacks, and drift eliminators. The tower costs do not include supply pumps or underflow pumps. The aeration basins are rectangular with a depth of 3.5 m (12 ft). The diffused air supply system was sized for 14 sLm/m^2 (5 scfm/ft^2) of basin flow area.

Adsorption consists of three steel contactors in series with an initial supply of granular activated carbon. Activated carbon usage is based on six-month throwaway at a cost of \$1.50/kg (\$0.70/lb). Chlorination consists of a feed system (no basin) and a building for cylinder storage. A chlorine dose of 2 mg/L is assumed, and the cost of chlorine is \$0.35/kg (\$320/ton). Clearwell storage is above ground, with a capacity equal to 10 percent of the daily plant flow. The high lift pumping has a head of 12 m (40 ft). The estimated treatment cost does not include expenditures for land, slime or corrosion control, fences, off-gas handling, or carbon disposal.

Figures 31 through 36 give the total treatment cost in dollars per 1000 gallons of treated water as a function of operating flow. Each figure shows the 90 to 99 percent removal cost range in October 1980 dollars for aeration towers, aeration basins, and adsorption for an influent contaminant concentration varying from 1 to 1000 μg/L. The required aeration basin and tower volumes for costing purposes were computed as a function of the mean air-to-water ratios given in Table 15. The cost bands for aeration towers are relatively narrow because little economy-of-scale exists for operating these units at such small hydraulic loadings.

The activated carbon requirements were the mean values given in Table 16. The adsorption cost ranges are wider than those estimated for aeration because of the influence of contaminant concentration. For example, the cost of 90 percent removal by aeration is theoretically the same whether the contaminant concentration is reduced from 1000 to 10 μg/L or from 1 to 0.1 μg/L. Adsorption capacity and activated carbon usage, however, vary with contaminant concentration; therefore, the cost of 90 percent removal by activated carbon is higher if the influent concentration is 1000 μg/L compared to 100 μg/L. The cost range for adsorption is very wide for some contaminants because of poor adsorbability. To achieve high percentages of removal for the poorly adsorbed contaminants, a large amount of activated carbon is required, and this dramatically increases the cost of treatment.

Figure 37 illustrates another way of presenting the cost information given in Figures 31 to 36. The total treatment cost of trichloroethylene removal is shown as a function of influent concentration at four levels of effluent concentration for each of the three treatment modes. Similar graphs could be generated for the other contaminants. Figure 38 gives the total treatment cost of trichloroethylene removal versus treatment plant

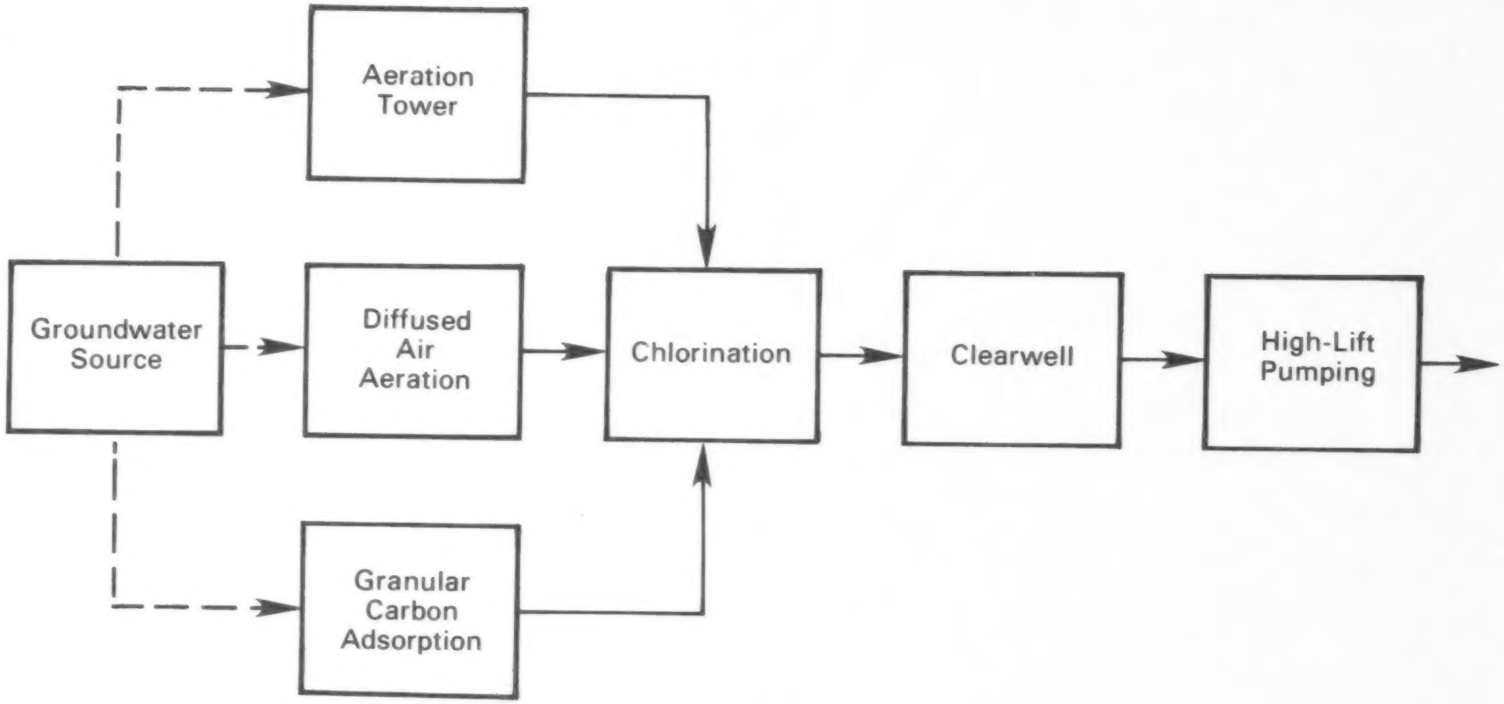
Groundwater Source
Aeration Tower
Diffused Air Aeration
Granular Carbon Adsorption
Chlorination
Clearwell
High-Lift Pumping

Figure 30. Water Treatment System Configuration for Economic Analysis of Volatile Organic Contaminant Removal.

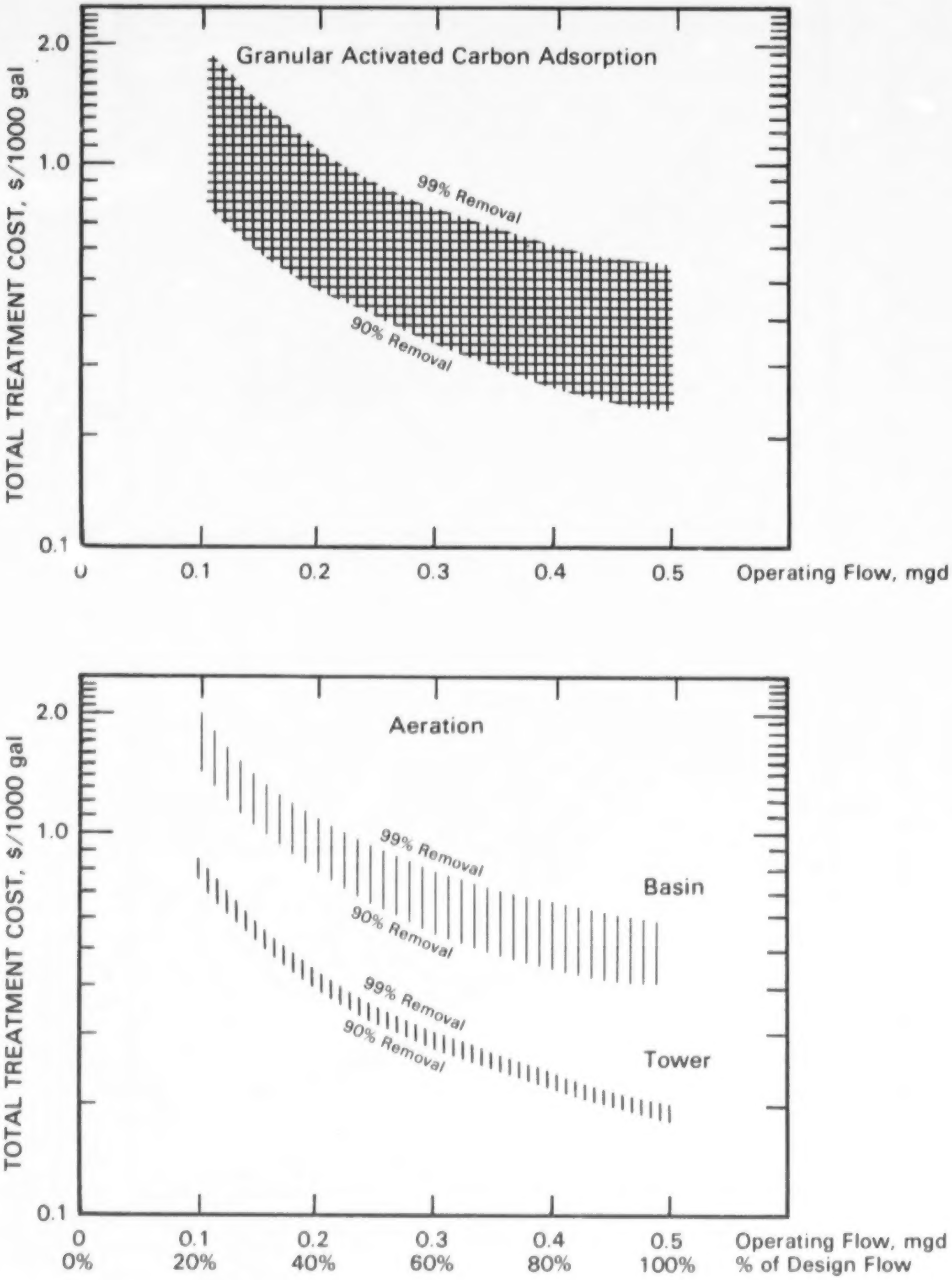

Figure 31. Cost of Trichloroethylene Removal (90-99%) (October 1980 Dollars, Influent Concentration of 1-1000 μg/L, Design Flow of 0.5 mgd).

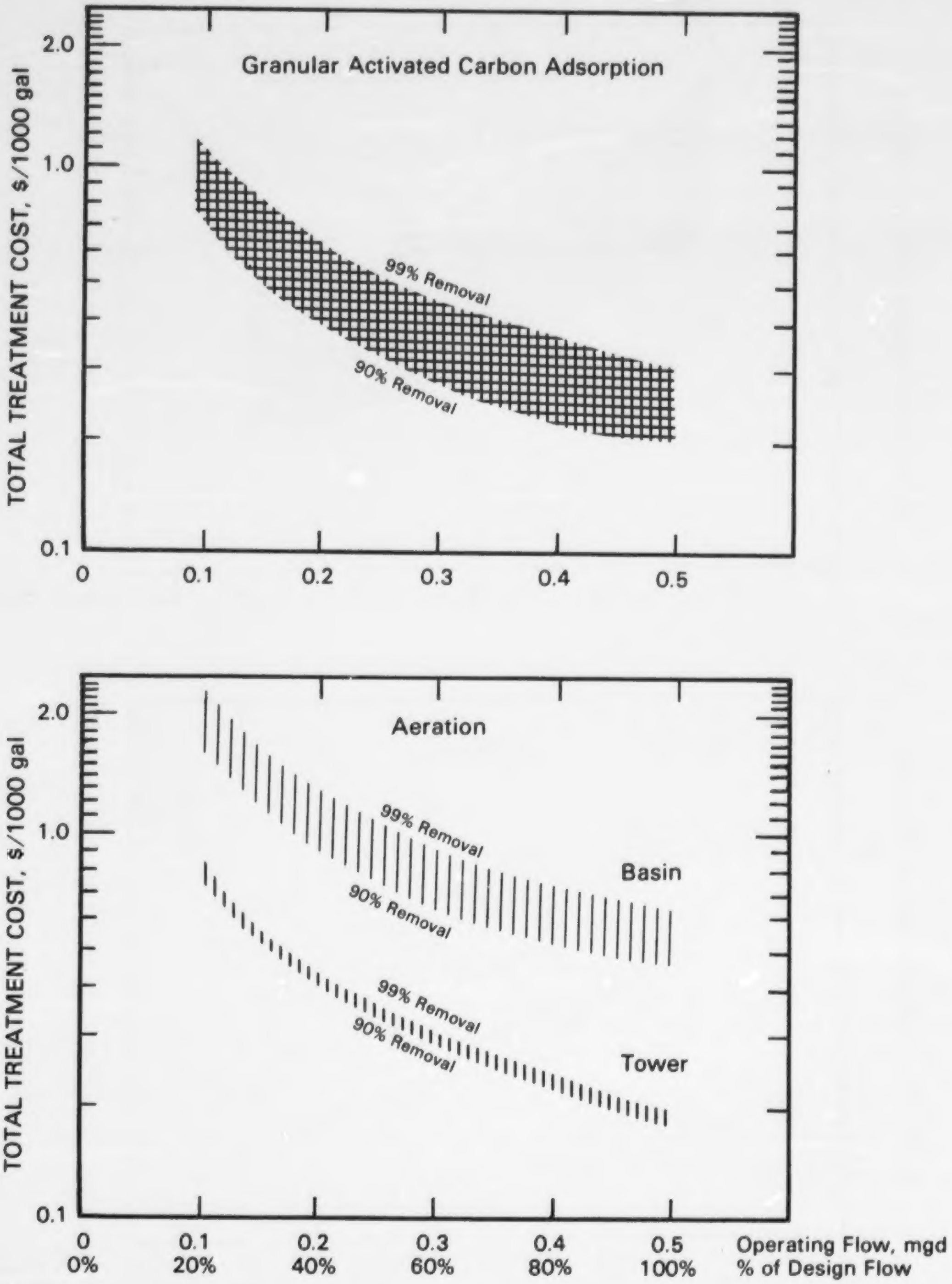

Figure 32. Cost of Tetrachloroethylene Removal (90-99%) (October 1980 Dollars, Influent Concentration of 1-1000 μg/L, Design Flow of 0.5 mgd).

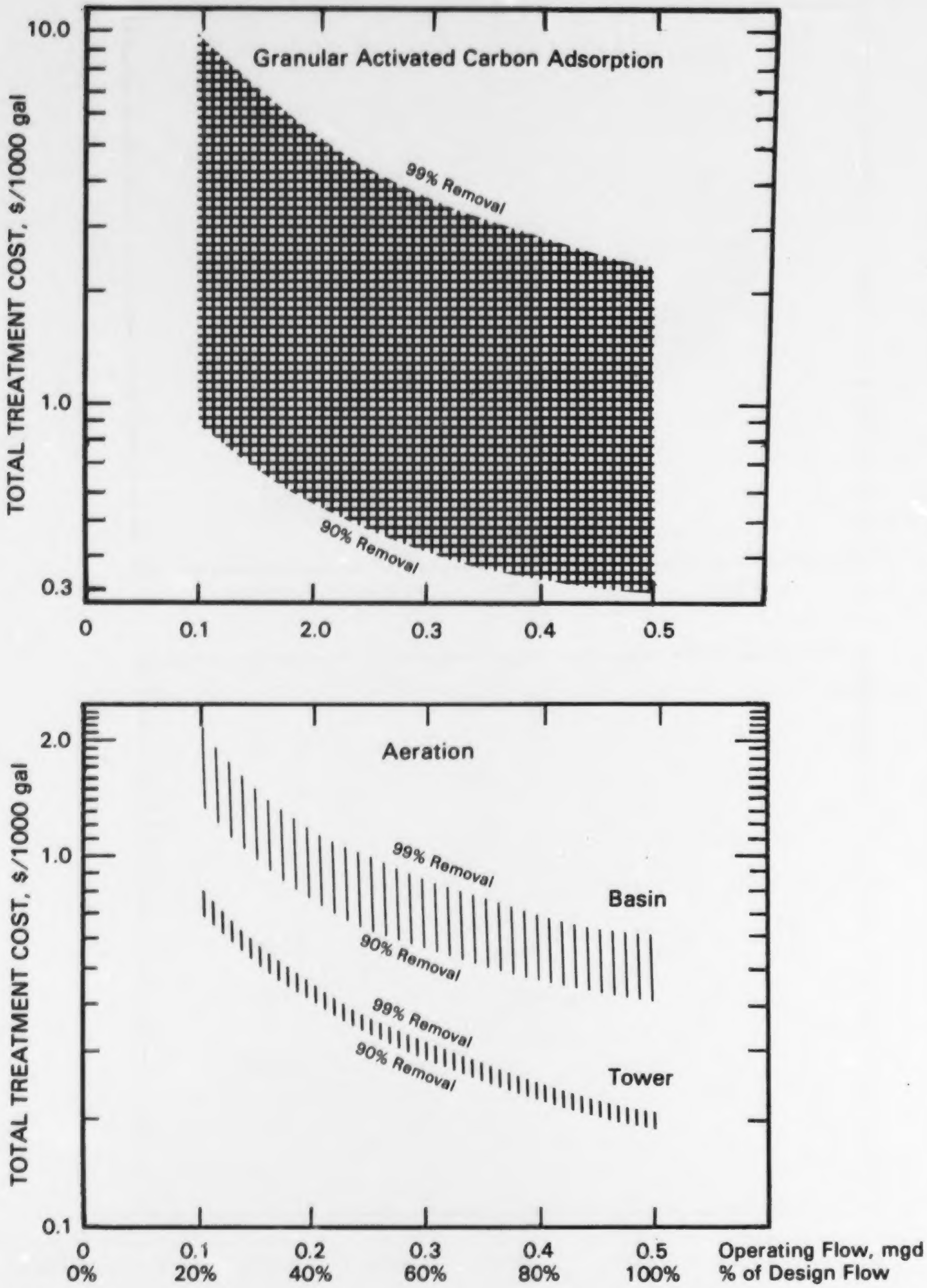

Figure 33. Cost of 1,1,1-Trichloroethane Removal (90-99%) (October 1980 Dollars, Influent Concentration of 1-1000 µg/L, Design Flow of 0.5 mgd).

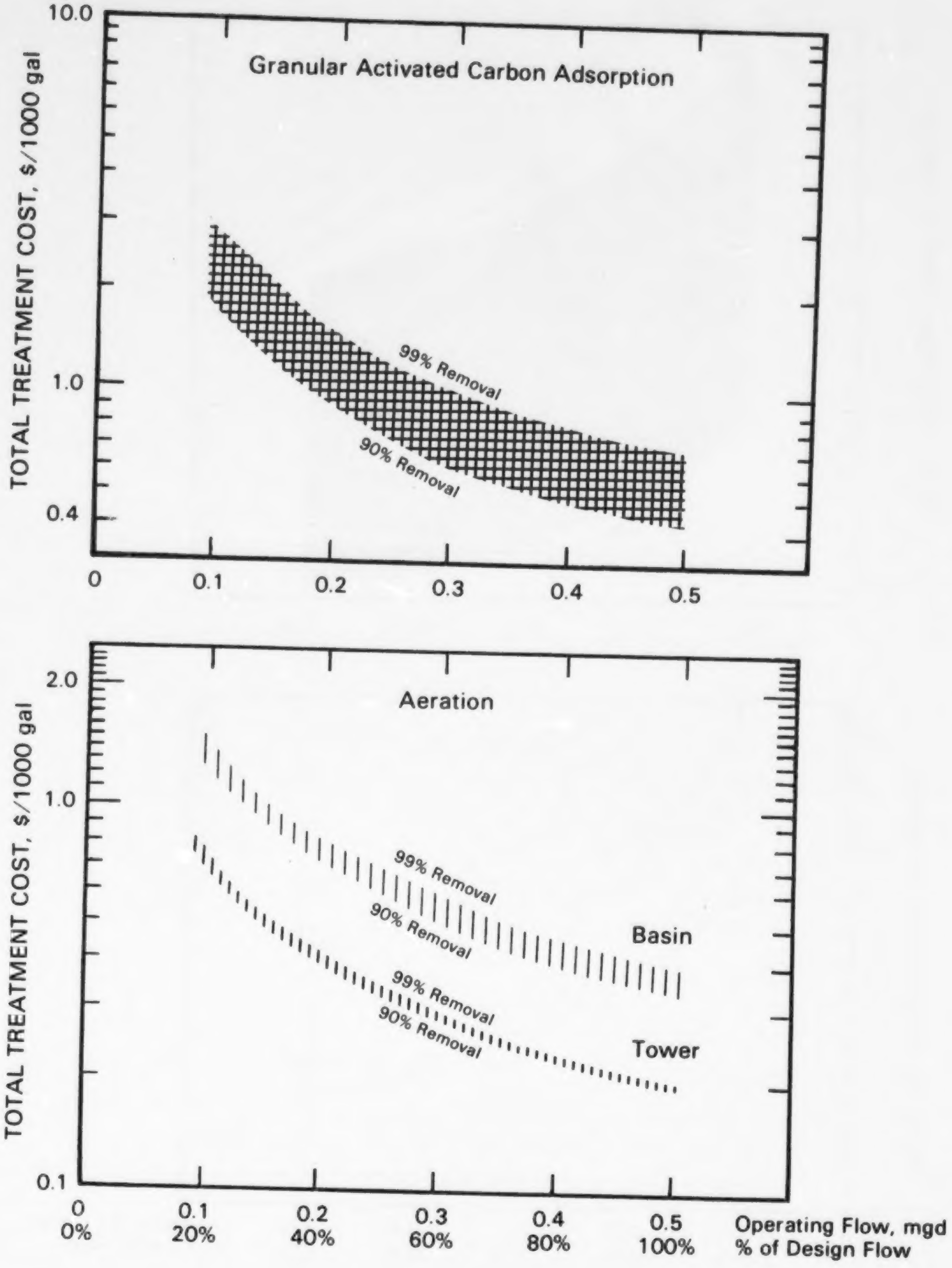

Figure 34. Cost of Carbon Tetrachloride Removal (90-99%) (October 1980 Dollars, Influent Concentration of 1-1000 μg/L, Design Flow of 0.5 mgd).

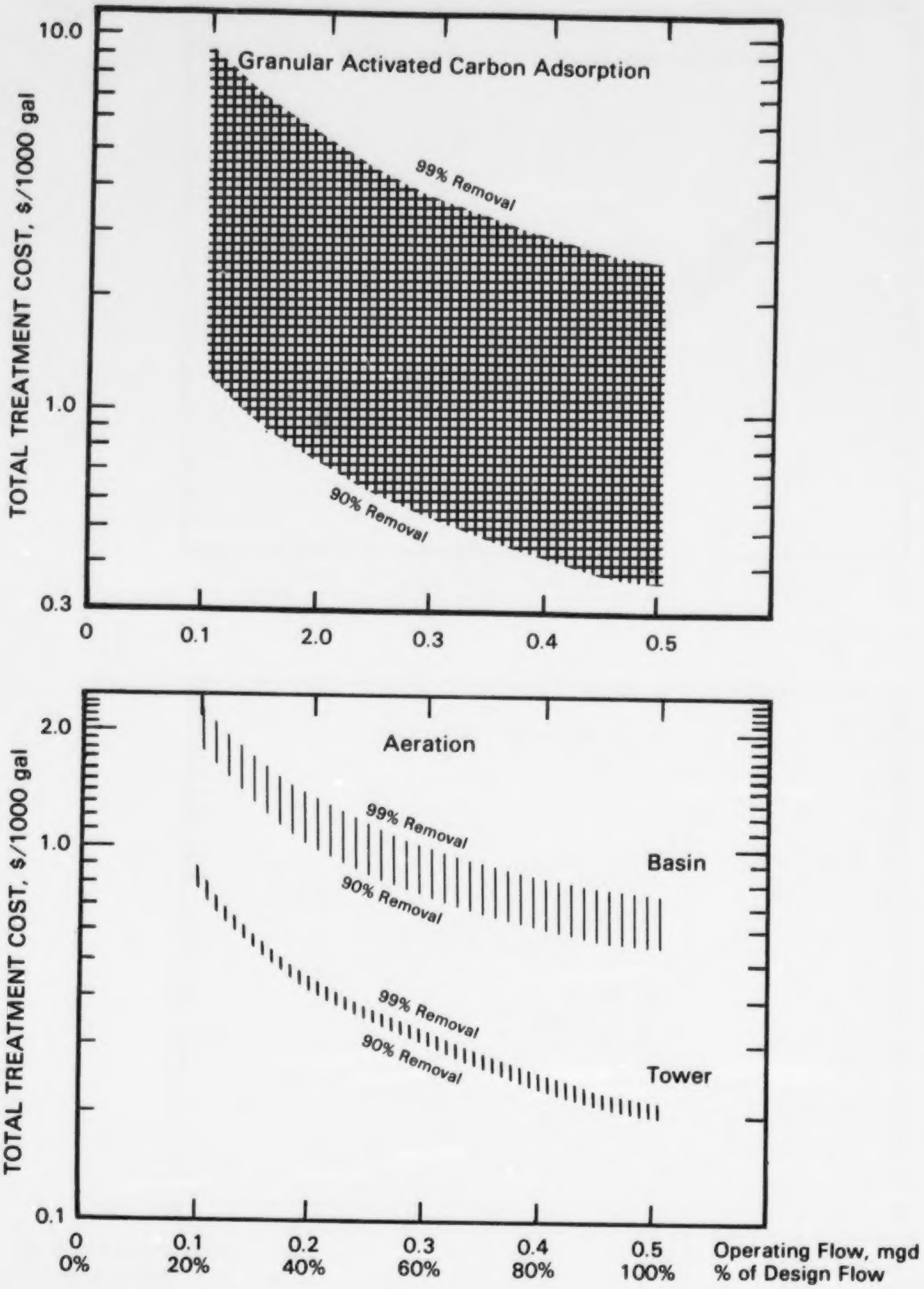

Figure 35. Cost of Cis-1,2-Dichloroethylene Removal (90-99%) (October 1980 Dollars, Influent Concentration of 1-1000 µg/L, Design Flow of 0.5 mgd).

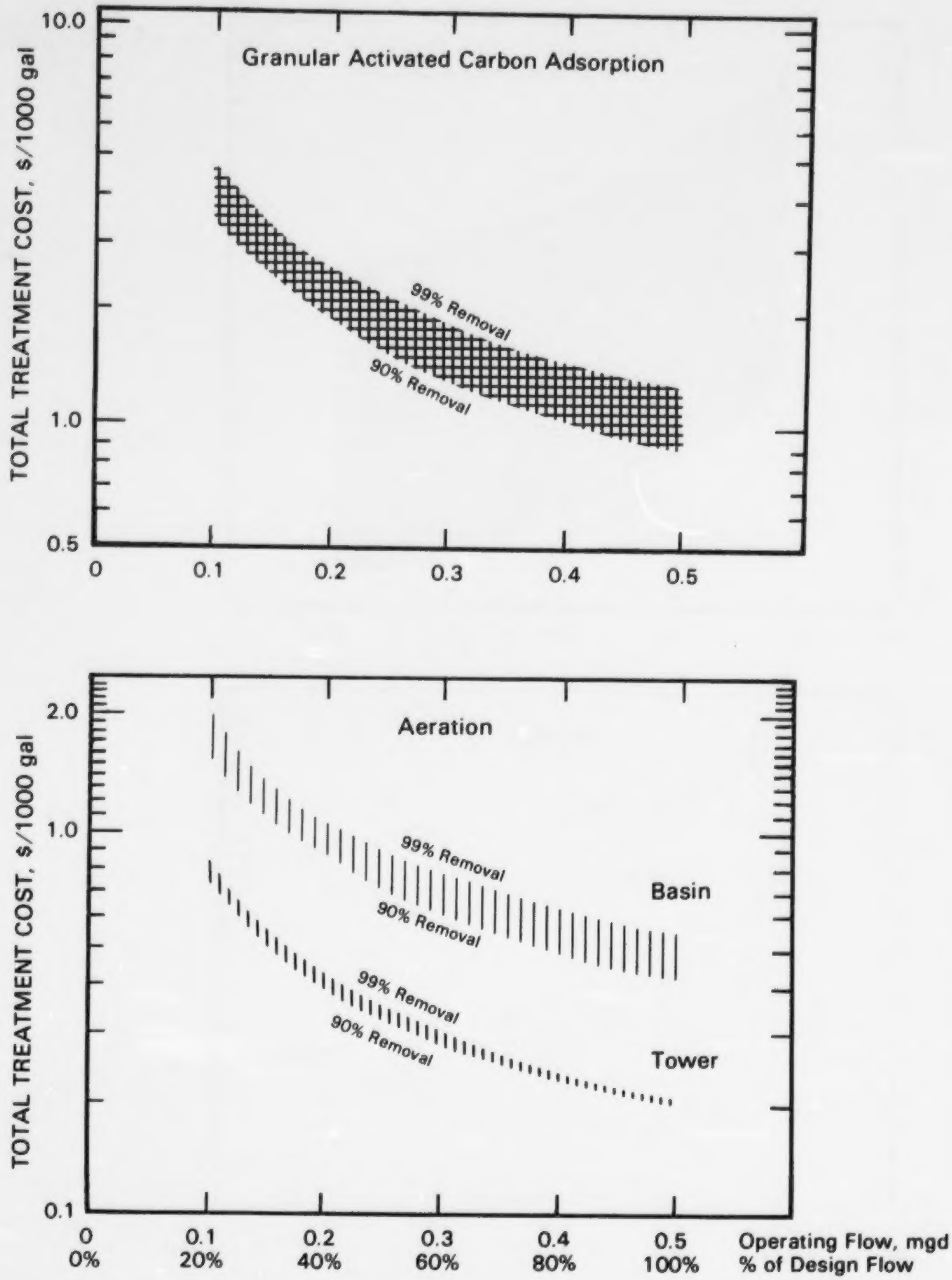

Figure 36. Cost of 1,2-Dichloroethane Removal (90-99%) (October 1980 Dollars, Influent Concentration of 1-1000 μg/L, Design Flow of 0.5 mgd).

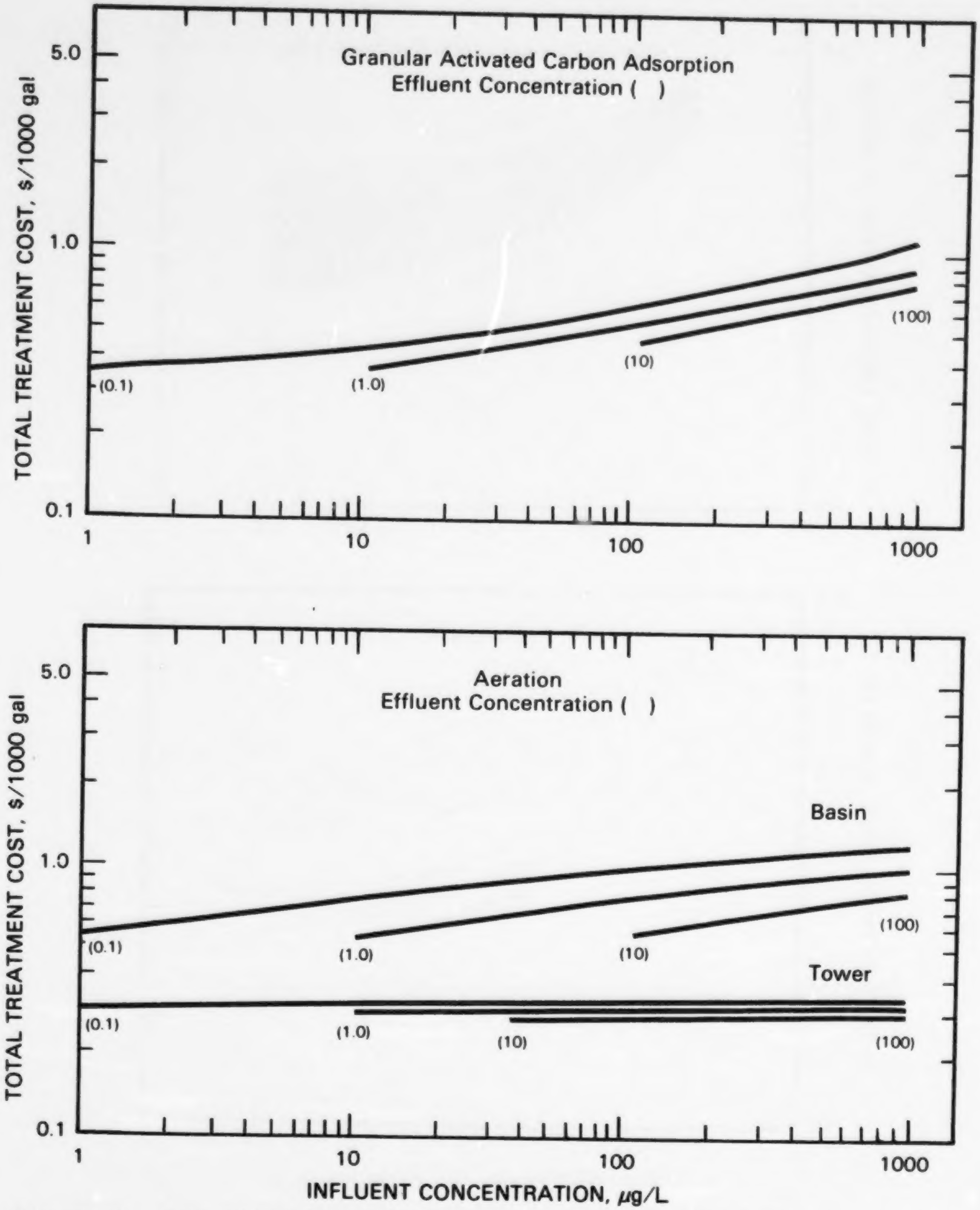

Figure 37. Cost of Trichloroethylene Removal (October 1980 Dollars, Effluent Concentrations of 0.1-100 μg/L, Design Flow of 0.5 mgd, Operating at 60% Capacity).

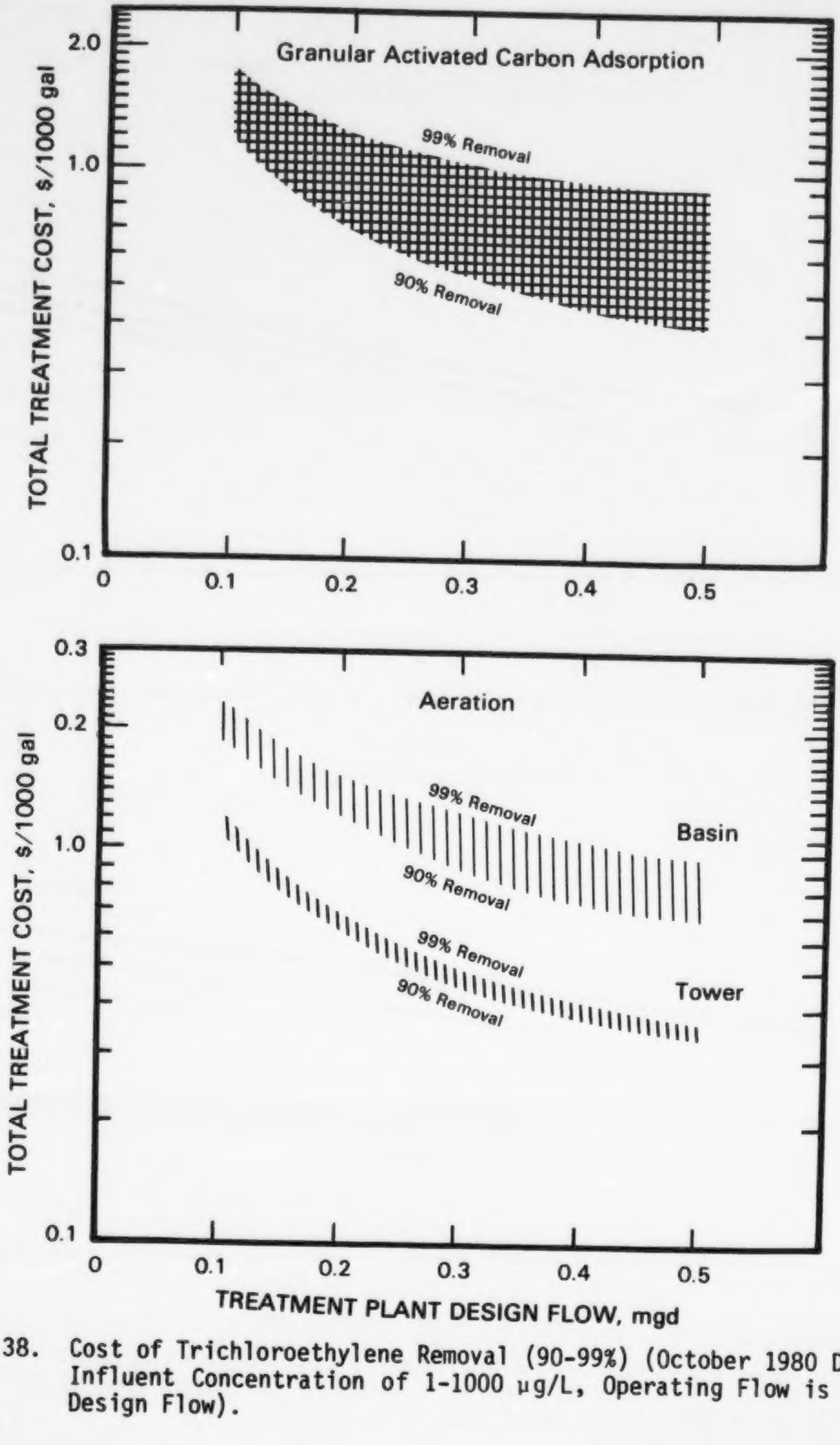

Figure 38. Cost of Trichloroethylene Removal (90-99%) (October 1980 Dollars, Influent Concentration of 1-1000 µg/L, Operating Flow is 50% of Design Flow).

size for each treatment type. Operating flow is 50 percent of design flow for these data, with an influent concentration of 1 to 1000 µg/L. Similar cost information can be generated for the other contaminants. Note in these estimates that operating a small treatment system at less than design flow has a pronounced effect on unit costs.

As in any economic analysis, the cost data presented here are dependent on the particular design assumptions that were made for the treatment system. For example, the costs associated with both types of aeration are quite sensitive to the removal efficiencies. The cost of treatment, therefore, can vary significantly depending on the design parameters selected by the cost analyst and on site-specific considerations. For this reason, these cost estimates should be viewed only as a preliminary attempt to quantify the economics of removing trichloroethylene and related solvents from drinking water.

SECTION 6

SUMMARY

Volatile organic chemicals occur in both untreated and treated drinking water. In general, ground waters rather than surface waters are more likely to have significant concentrations of these compounds. Some exceptions might be during periods when a river is frozen over and volatile organics cannot escape into the atmosphere, when upstream "spills" occur, or when products used to treat or transport the water have contaminants.

The seriousness of having these organics in one's drinking water and the establishment of acceptable limits are current topics of concern at USEPA (1) that may not be resolved for some time. In the interim, however, research is striving to better understand the effectiveness of different water treatment processes to see what degree of volatile organic removal is achievable so a utility can better assess the option of seeking an alternative source or providing treatment.

Although conventional treatment (coagulation, sedimentation, and filtration) has been found to be largely ineffective for their control, these organics can, however, be removed by aeration, adsorption on granular activated carbon or synthetic resins, or combinations of these processes. Aeration, for example, preceding adsorption, seems very encouraging (Figure 28) and may be the combination needed for treating certain problem waters. Because treatment information is lacking for many of the organic compounds being found in drinking water, USEPA is continuing to gather data on the effectiveness of the aeration and adsorption processes, as well as beginning treatment studies on the effects of strong oxidants, such as ozone, and the process of reverse osmosis. Boiling (vigorously for five minutes) can also be effective for removing most of these organic compounds. Where treatment data were available, preliminary estimates of treatment costs show significant variations between process and contaminants and amplify the need for a thorough organic analysis and site-specific experimental data.

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